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EXPERIMENTAL INVESTIGATION OF ACOUSTIC LINERS TO SUPPRESS SCREECH IN STORABLE PROPELLANT ROCKET MOTORS

by David W. Vincent, Bert Phillips, and John P. Wanhainen

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SUMMARY

Several acoustic liners (Helmholtz type) were experimentally and theoretically evaluated to determine their effectiveness to suppress screech in a rocket motor. The liners were experimentally rated in a storable propellant (N_2O_4 -50 percent hydrazine, 50 percent UDMH) rocket at a nominal chamber pressure of 100 psia (689 kN/m^2) and 6700 pounds of thrust (29.8 kN). Liner design variables investigated included aperture size, liner percent open area, liner length, and aperture shape. Tests were conducted in both a marginally stable and a spontaneously unstable combustor. Bomb pulses were used to rate stability in terms of the grains (grams) of explosive necessary to induce instability.

Bomb pulses as high as 170 psi (1172 kN/m^2) peak-to-peak were damped by liners when the liner resonant frequency was near the screech frequency. Calculated theoretical absorption coefficients assuming both flow and no flow past the apertures agreed with the experimental results. Full-length liners were not required for stabilization. Aperture size and shape had secondary effects. Longitudinal slots, which would be adaptable to regeneratively cooled configurations, were found to be as effective as circular apertures in suppressing screech.

INTRODUCTION

Historically, the use of perforated plate acoustic liners in combustors as a means of suppressing high-frequency oscillatory combustion is not new. As early as 1953, liners were successfully used to suppress acoustic mode combustion instability in ramjets and afterburning turbojets (refs. 1 to 3) and more recently in rockets (refs. 4 and 5). However, the problem of adapting Helmholtz resonator theory to the conditions in rocket combustors still exists. Calculated theoretical absorption coefficients necessary to eliminate screech in rockets cannot be predicted and must be determined through

experimental tests. As indicated in reference 5, problems in liner design arise in specifying the effective flow past the apertures as well as the properties of the gases behind the liner. This investigation was undertaken (1) to evaluate the effects of the liner design variables, (2) to determine the minimum absorption coefficient necessary to suppress screech, and (3) to experimentally verify the effects of flow past the apertures on absorption characteristics of liners in rockets using storable propellants, that is, nitrogen tetroxide and 50 percent hydrazine - 50 percent unsymmetrical dimethyl hydrazine (UDMH). A similar study was reported in reference 5 using a hydrogen-oxygen propellant combination. The liner design variables investigated included percent open area (perforated area/total liner surface area), aperture diameter, liner length, and aperture shape.

The investigation reported herein was conducted at the Propulsion Systems Laboratory using a 10.77-inch (27.36-cm) diameter thrust chamber at a nominal chamber pressure of 100 psia (689 kN/m²). The nominal thrust level of the combustor was 6700 pounds (29.8 kN). Stability rating of the various liner configurations was accomplished by subjecting the combustor to tangential pressure pulses generated by various size RDX explosive charges. In addition, the various liner configurations were tested in a spontaneously unstable combustor.

APPARATUS

Facility

The tests were conducted in the Propulsion Systems Laboratory which is capable of simulating altitudes to 100 000 feet (30 480 m). The rocket combustors were fired horizontally as shown in figure 1. Although not a test requirement, test cell pressure was set at 1 psia (6.9 kN/m²) because of the toxic propellants and minimization of base pressure effects on thrust measurements required for performance calculations. The facility utilized a pressurized system to deliver propellants to the combustor from the two 560-gallon (2.12-m³) run tanks.

Combustor. - A typical heat-sink combustor consisted of an injector, acoustic liner assembly, bomb ring, and convergent-divergent exhaust nozzle. The injector (fig. 2) used in this investigation was a flat-face, fuel-oxidant-fuel triplet with film-cooling fuel jets on the circumference. Two combustor configurations incorporating the injector (shown schematically in fig. 3) were used in the study. The 42-inch (106.7-cm) L* heat-sink combustor was 23.8 inches (60.4 cm) long from the injector to the throat. Increasing the L* of the combustor to 56 inches (142.2 cm) was accomplished by replacing the bomb ring with a 10-inch (25.4-cm) cylindrical section which made the total length 30.5 inches (77.47 cm). The combustor inside diameter was 10.77 inches (22.36 cm). The exhaust

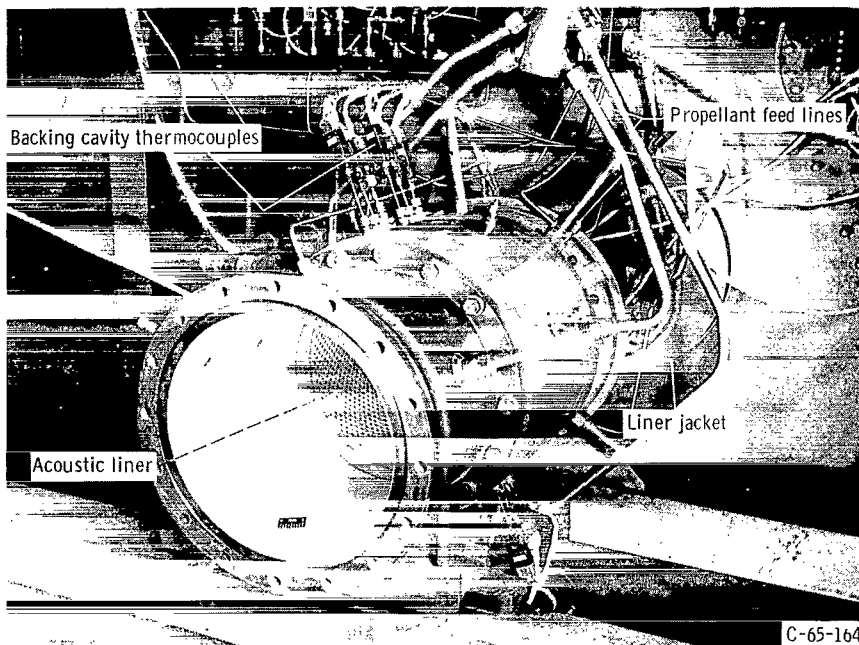


Figure 1. - Combustor assembly mounted horizontally in test stand. Nozzle is removed to expose 1/8-inch (0.32 cm) diameter aperture, 10-percent open area liner.

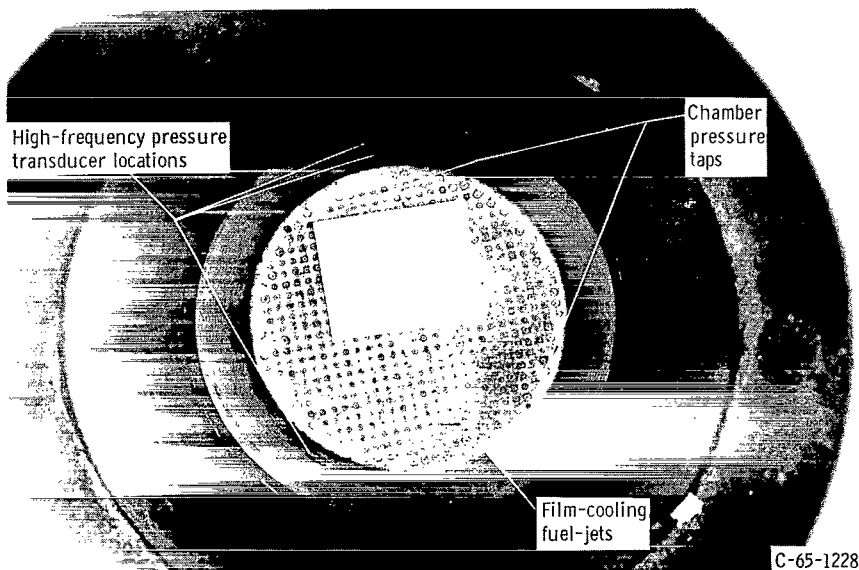
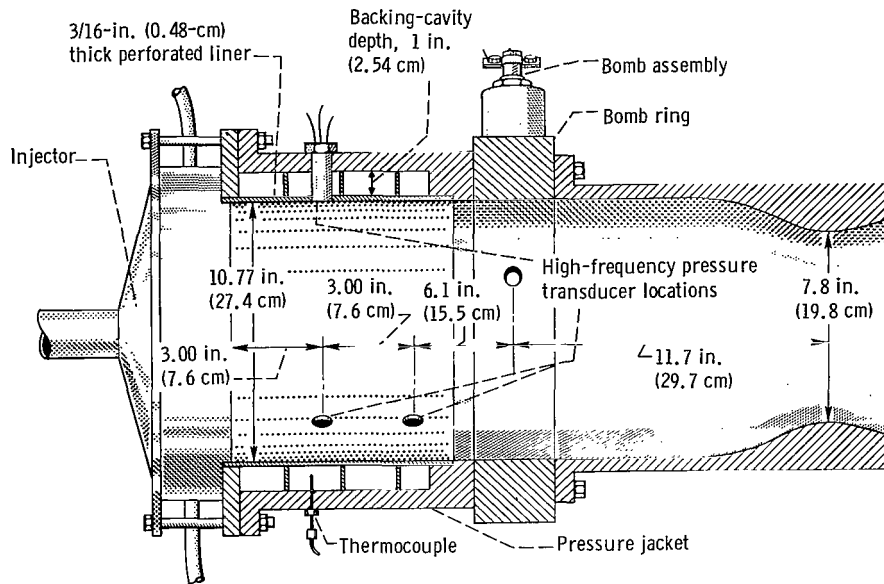
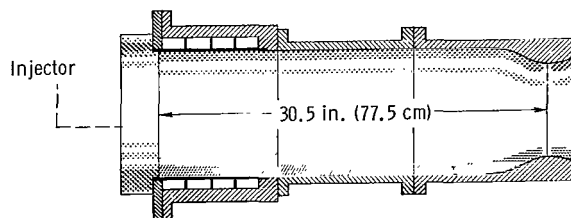


Figure 2. - Combustion chamber assembly with liner installed. View looking toward injector. Injector details: 487 elements, fuel - oxidant - fuel with 54 fuel jets for film cooling. Oxidant orifice diameter, 0.035 inch (0.089 cm); fuel orifice diameter, 0.018 inch (0.046 cm); impingement angle, approximately 40°.



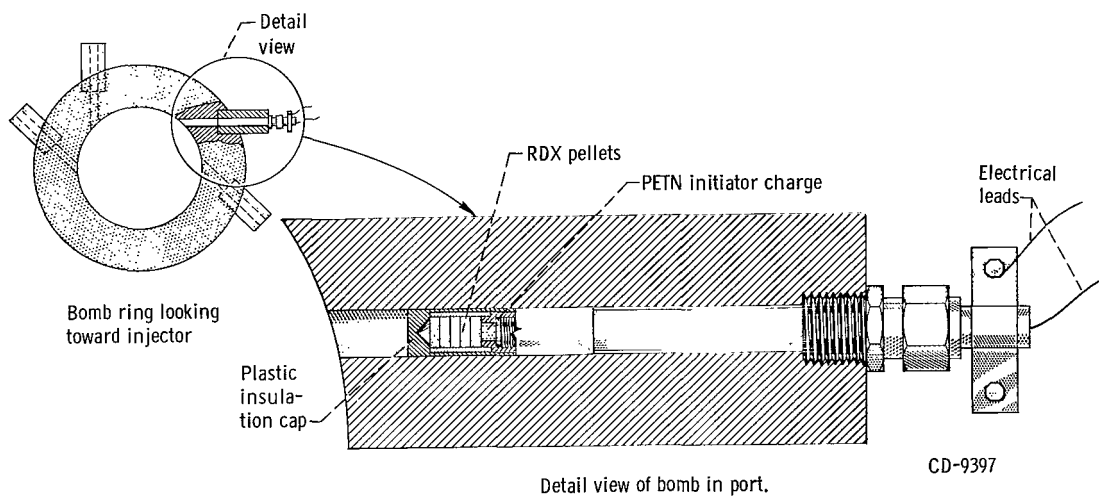
(a) 42-Inch (106.7 cm) chamber combustor.



(b) 56-Inch (142.2-cm) chamber combustor. Detail same as 3(a) except for additional chamber section and no bomb ring.

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Figure 3. - Combustor configurations.



Detail view of bomb in port.

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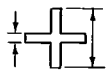
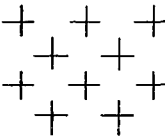
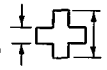
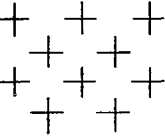
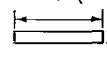
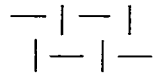
Figure 4. - Bombing and explosive bomb used for pulse rating lines.

TABLE I. - LINER CHARACTERISTICS

(a) Circular apertures

Aperture diameter		Open area, percent	Liner length	
in.	cm		in.	cm
1/8	0.32	2.5	8	20.3
		5	8	20.3
		10	8	20.3
1/4	0.64	5	8	20.3
		10	8	20.3
		20	8	20.3
1/8	0.32	10	2	5.1
			4	10.1
1/4	0.64	10	4	10.1

(b) Noncircular apertures

Aperture geometry	Aperture dimensions				Aperture pattern	Open area, percent	Liner length	
	Length		Width				in.	cm
	in.	cm	in.	cm				
Longitudinal slots	7½	19.05	1/16	0.16	34 slots; 1-in. (2.54-cm) spacing	5	8	20.3
			1/8	0.32	34 slots; 1-in. (2.54-cm) spacing	11	8	20.3
			3/16	0.48	34 slots; 1-in. (2.54-cm) spacing	16.5	8	20.3
Cross	1/32 in. (0.09 cm)  3/16 in. (0.48 cm)					10	8	20.3
	1/8 in. (0.32 cm)  1/4 in. (0.64 cm)					10	8	20.3
Alternating slits	13/32 in. (1.03 cm)  1/16 in. (0.16 cm)					10	8	20.3

nozzle had a contraction ratio of 1.89 and an expansion ratio of 1.3. This nozzle was chosen because the losses were more accurately predictable for performance calculations than would be the case for a large expansion ratio nozzle (ref. 6). The heat-sink bomb ring had four tangentially directed ports (fig. 4). Hot-gas surfaces of the heat-sink combustors were flame sprayed with 0.012 inch (0.030 cm) of Nichrome and 0.018 inch (0.046 cm) of zirconium oxide to reduce heat transfer to the mild steel. The coating normally allowed a 3-second run duration without damaging the combustor.

Liner assembly. - The liner assembly, shown as part of the combustor in figure 3, consisted of a heat-sink pressure jacket and a removable mild steel acoustic liner. The backing-cavity depth and the liner thickness were held constant at 1 and 3/16 inch (2.54 and 0.48 cm), respectively. Liner percent open area, liner length, and aperture size and shape were varied as indicated in table I. Circumferential partitions in the liner backing cavity were used to minimize recirculation gas flow behind the liner which in turn reduced the flow through the apertures. Initially, the liners were fabricated with only one partition; however, during later testing three partitions were used to improve structural support and prevent excessive liner warpage. Presented in figure 5 is a photograph of a typical perforated liner with three partitions. Figures 5(b) and (c) are photographs of liners using axial slot and cross shaped apertures.

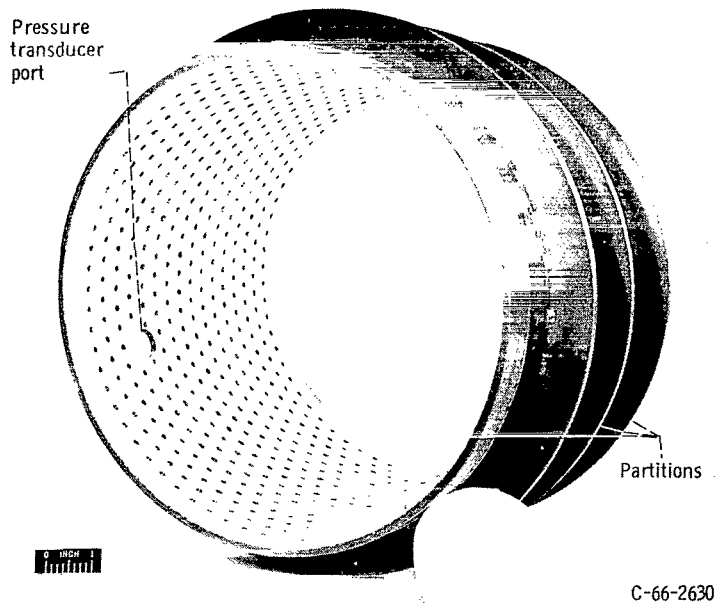
Instrumentation

Combustor operating parameters were recorded on an automatic digital data system and on a direct writing oscillograph. Strain gage transducers were used to measure steady-state pressures, and turbine flowmeters for propellant flow rates. The transducers were calibrated electrically prior to engine firing. Backing-cavity-gas temperature was measured using open ball, tungsten - tungsten-26-percent-rhenium thermocouples.

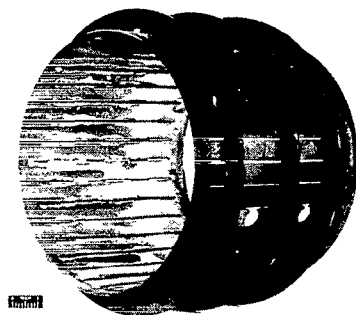
Water-cooled, piezoelectric high-frequency response pressure transducers were flush mounted at three positions in the combustor (fig. 3) to determine the frequencies and amplitudes of the instabilities. The response of the transducers (as installed) was flat to 6000 hertz and had a resonant frequency of 20 000 hertz. Signals from the high-frequency transducers were recorded in analog form on magnetic tape, then replayed at reduced tape speed on an oscillograph for initial analysis.

The frequency analyzer used to obtain the amplitude spectral density graphs presented in this report was a heterodyne frequency analyzer. Since the amplitude spectral density graphs shown in the RESULTS AND DISCUSSION section are Fourier analyses of the data, spectral lines of lower amplitudes may occur at exact multiples of the predominant frequency in the figures. This characteristic will be discussed further as part of the data analysis.

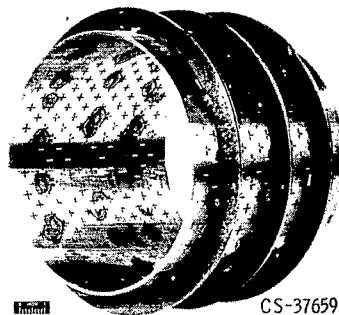




(a) Circular apertures: 1/8-inch (0.32-cm) diameter; 5-percent open-area liner.



(b) 1/16-inch (0.16-cm) wide longitudinal slot liner.



(c) Cross-shaped aperture liner.

Figure 5. - Examples of liners tested in this investigation.

PROCEDURE

All liner configurations were tested with the same injector at 100-psia (689-kN/m^2) chamber pressure and oxidant-fuel mixture ratios (O/F) of 1.6 and 2.0. Shown in figure 6 is a typical trace of propellant flows and chamber pressure during a typical firing. About 2 seconds were needed for the combustor to achieve steady-state conditions. Total run duration of each test was about 3 seconds which prevented the heat-sink hardware from being damaged; therefore, several tests could be made with the same hardware. Each liner was stability rated in combustors with characteristic lengths L^* of 42 and 56 inches (106.7 and 142.2 cm).

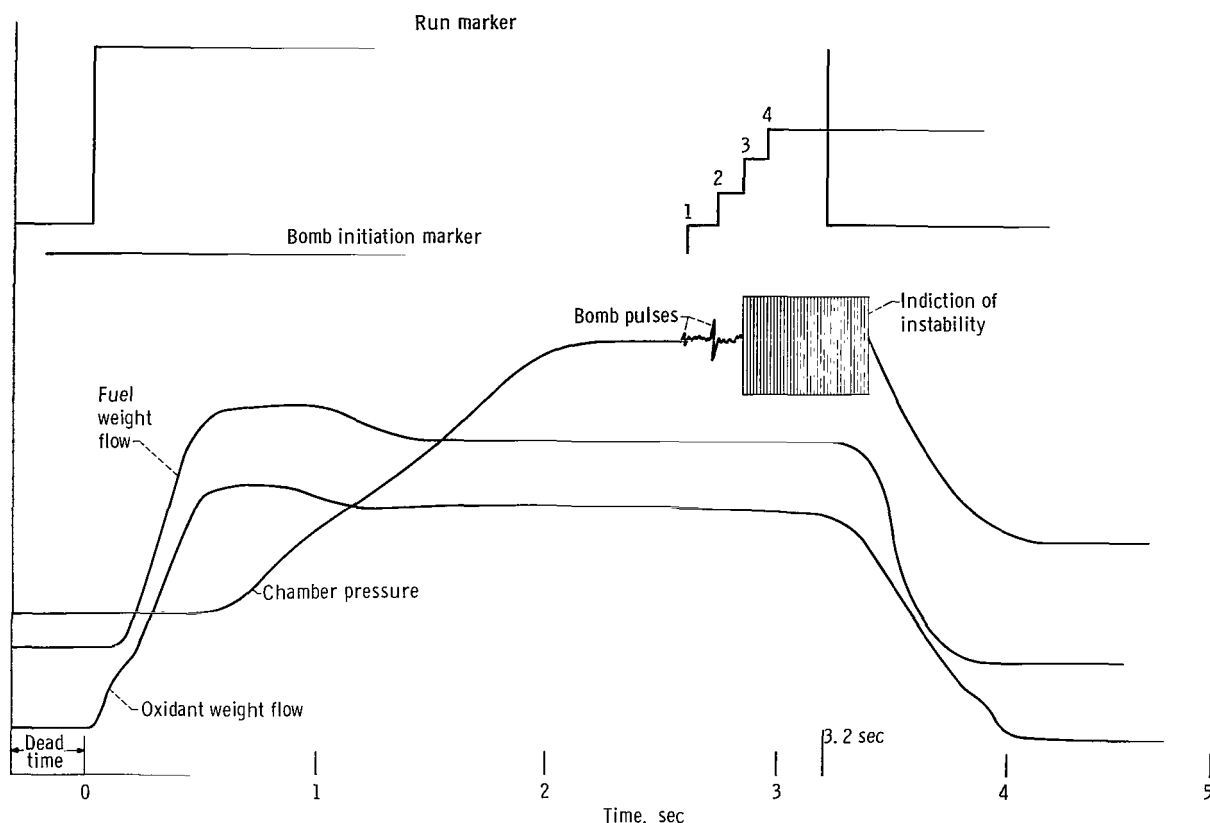


Figure 6. - Oscillograph trace of typical combustor test.

An electronic controller regulated propellant flow rates (maintaining constant chamber pressure and mixture ratio throughout the firing), and program timers sequenced propellant valves and the firing of RDX bombs.

42-Inch (106.7-Cm) Characteristic-Length Combustor Ratings

Rating liners in the marginally stable combustor ($L^* = 42$ in. (106.7 cm)) was accomplished by detonating RDX bombs in the bomb ring, shown in figure 4, (further description of bombs can be found in ref. 7). The bomb ring was located immediately downstream of the liner (about 10 in. (25.4 cm) from the injector). The four charges were usually successively larger and were fired during combustor steady-state operation. All charges were fired sequentially at approximately 100 millisecond intervals even though screech may have been initiated. The 100-millisecond interval allowed ample time for each pulse to damp before the following charge was exploded. Determination of the bombs that were damped or the one that initiated screech was accomplished by analyzing the oscillograph traces of the output of the flush mounted high-frequency transducers.

56-Inch (142.2-Cm) Characteristic-Length L^* Combustor Rating

As will be discussed later, the 56-inch (142.2-cm) L^* combustor configuration was spontaneously unstable without a liner, so the liners were rated by determining the reduction of screech amplitude. This was accomplished using spectral density graphs made of the high-frequency pressure transducer output.

RESULTS AND DISCUSSION

The experimental and analytical evaluation of several array Helmholtz resonator acoustic liners are presented in this report. Experimentally, the effect of liner variables (i. e. , percent open area, aperture diameter and shape, and liner length) were evaluated in terms of grains (grams) of RDX explosive that would damp in a marginally stable engine as well as in terms of the reduction in screech amplitude in a spontaneously unstable engine.

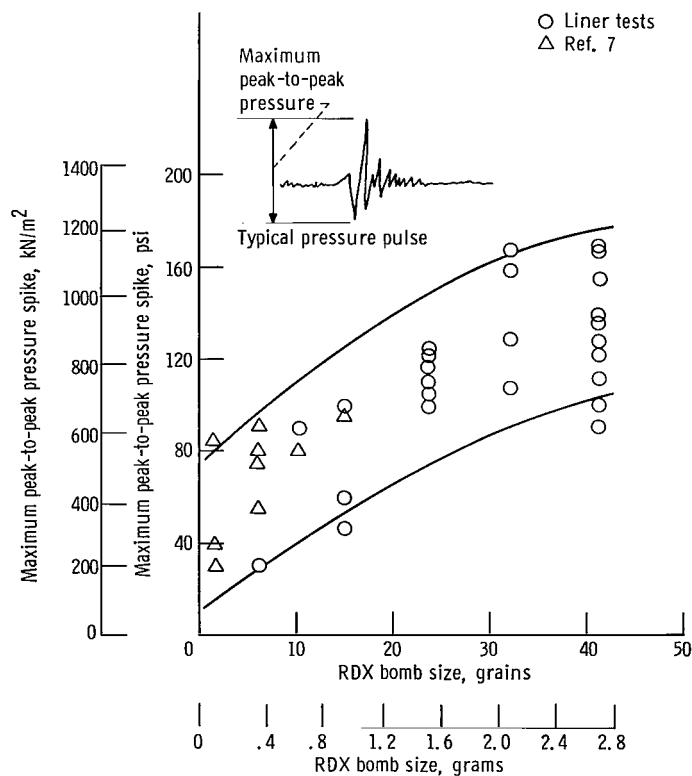


Figure 7. - Pressure spike produced by detonating various sized RDX bombs.

Analytically, the variables were evaluated using Helmholtz resonator theory such as in reference 8. The theoretical effectiveness of each liner is expressed in terms of liner resonant frequency and absorption coefficient (percent of the energy absorbed from the incident pressure wave). The acoustic theory is presented in the Theoretical Analysis section.

Grains (grams) of explosive rather than the bomb pressure time history amplitude was selected as a rating device because of extreme data scatter in the amplitude data (fig. 7). Variations in the amplitudes of the pressure pulses are quite common (refs. 7, 9, and 10) and may be due to changes in chemical augmentation, nonshock mounting of instrumentation, or instrumentation location.

Stability Characteristics of 42-Inch (106.7-Cm) Characteristic-Length

Combustor Without Liner

The stability characteristics of the 42-inch (106.7-cm) L^* combustor without an acoustic liner are shown in figure 8. Presented is the minimum charge size (grains (kg) of explosive) required to induce instability as a function of mixture ratio.

Each data point represents a separate test during which the combustor was bombed with increasing charge sizes until a sustained instability resulted. As seen in figure 8(a),

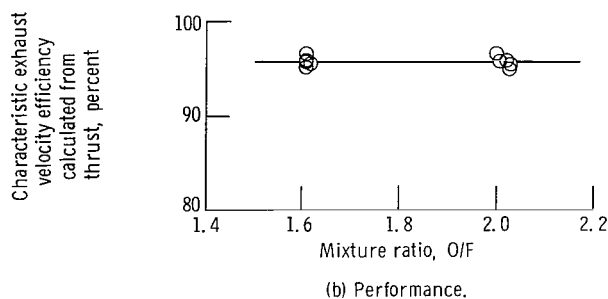
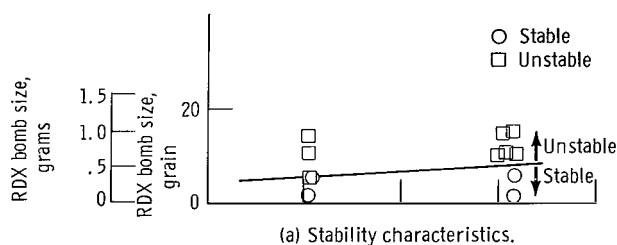
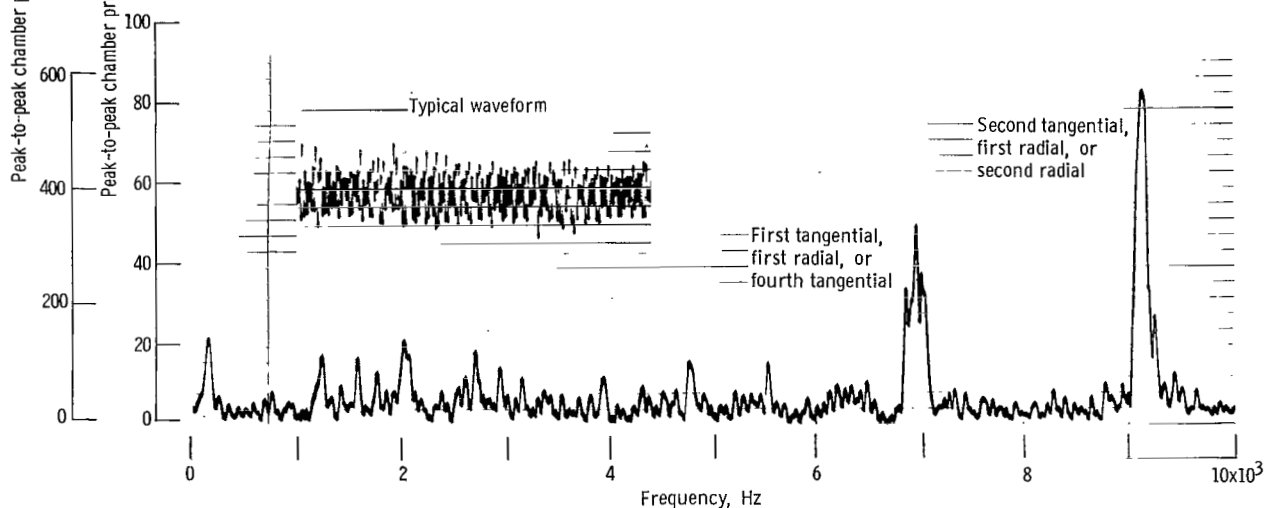
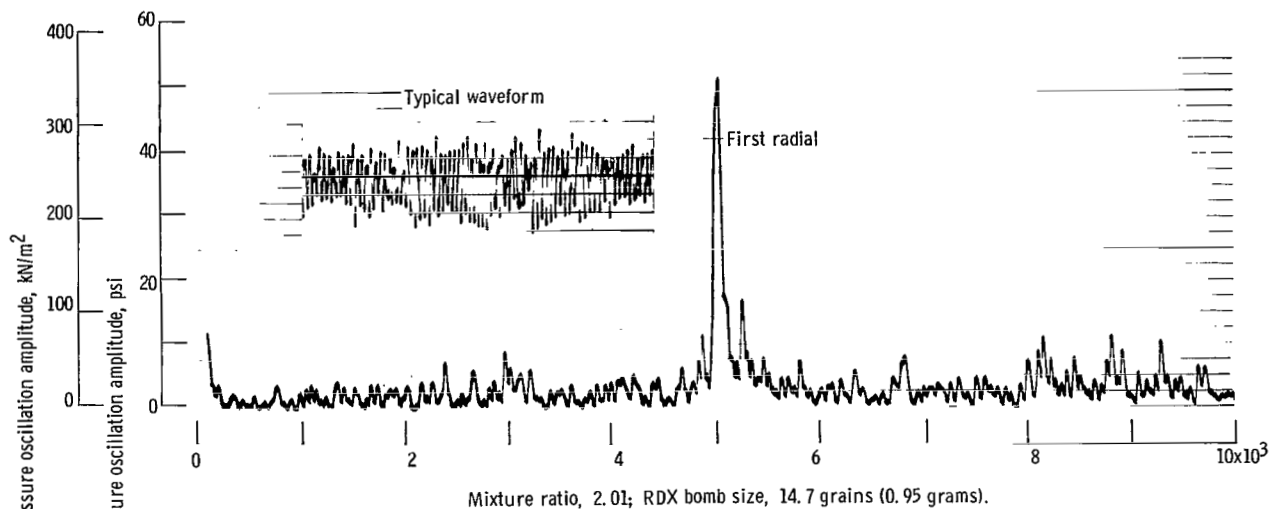


Figure 8. - Unlined combustor characteristics.
Chamber characteristic length, 42 inches
(106.7 cm).



(c) Typical spectral density of unlined combustor bombed unstable.

Figure 8. - Concluded.

at mixture ratios of 1.6 and 2.0, an average bomb size of 6 and 8 grains (0.39 and 0.52 g), respectively, were required to drive the combustor unstable. The C^* efficiency of the unlined combustor during stable operation was about 96 percent for both mixture ratios (fig. 8(b)). Spectral density graphs (fig. 8(c)) of the unstable combustion indicated that the predominant mode was first radial (5000 Hz) at a mixture ratio of 2.0 and changed to higher order modes at a mixture ratio of 1.6. Exact identification of the higher order modes was not possible with available instrumentation. The oscillation at 7000 hertz closely matches those calculated for either a fourth-tangential mode or a combined first-tangential and first-radial mode. The oscillation at a frequency of 9000 hertz corresponds

approximately to the second-radial mode, or it also could be a combined mode such as second tangential - first radial. In an attempt to further identify the modal oscillation characteristics, an examination of phase relations was not successful.

Effect of Aperture Diameter and Liner Percent Open Area in 42-Inch (106.7-Cm) Characteristic-Length Combustor

A series of aperture diameters and percent open areas were chosen after a preliminary analytical study. Using experience gained in a hydrogen-oxygen program (ref. 5), a backing-cavity-gas temperatures ranging from 1000° to 3000° R (556° to 1667° K) were assumed. The study resulted in the selection of 1/8- and 1/4-inch (0.32 and 0.64 cm) diameter apertures and a range of 5 to 20 percent open areas. The analysis showed that the liners would be tuned in a frequency range between 2500 to 5000 hertz. (See Theoretical Analysis of Circular Aperture Liners section for tuning calculations.) A liner with 1/8-inch (0.32-cm) apertures and 2.5-percent open-area ratio was added later in the program.

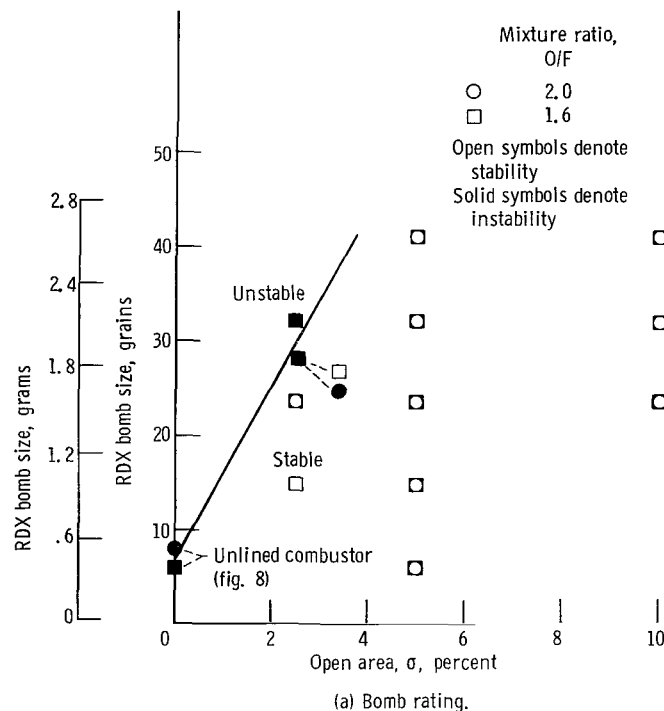
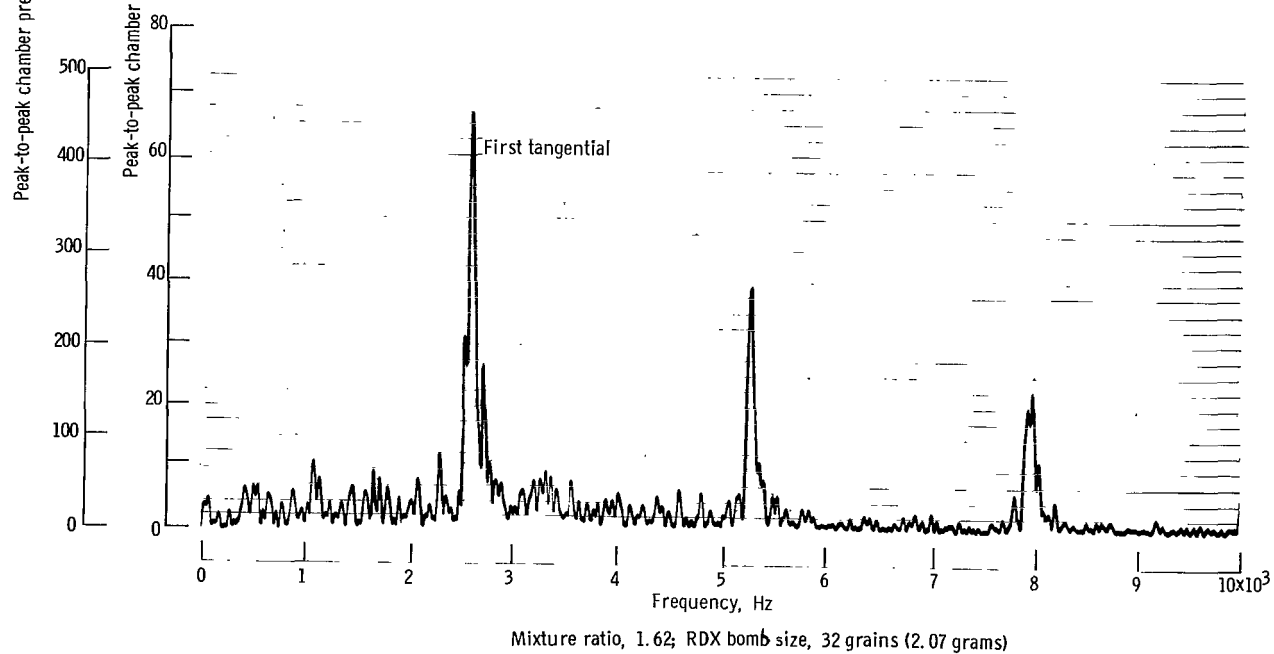
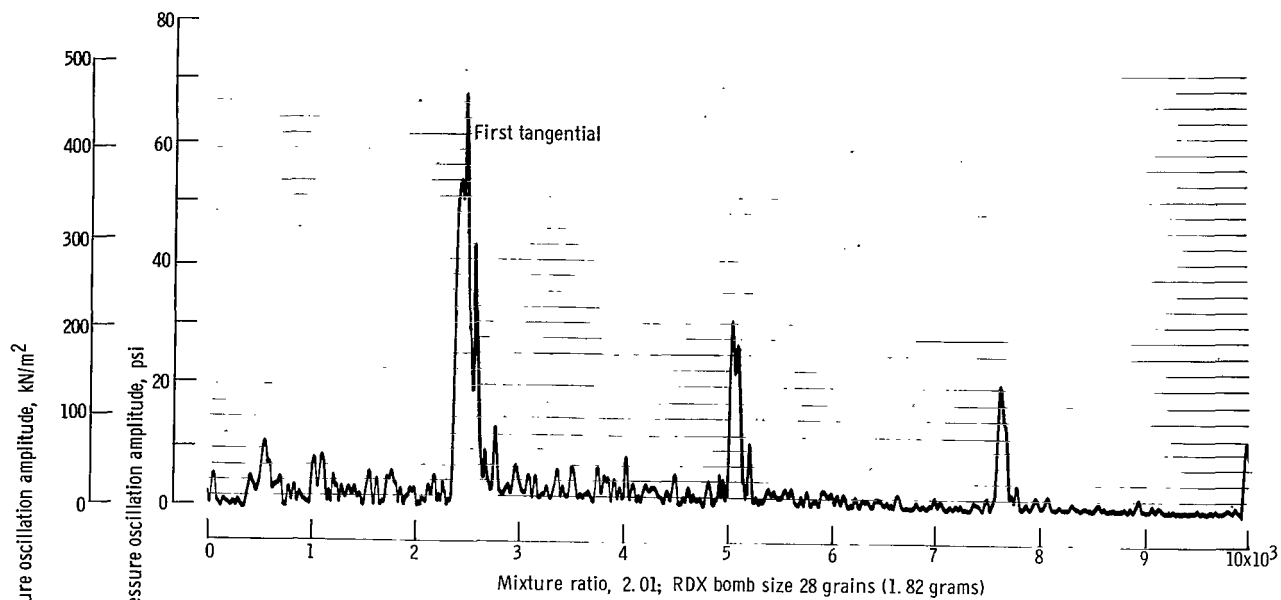


Figure 9. - Effects of experimental percent open area on combustor stability. Aperture diameter, 1/8 inch (0.32 cm); full length liner, 8 inches (20.3 cm); chamber characteristic length, 42 inches (106.7 cm).





(b) Typical spectral density graphs of induced instability. Liner open area, 2.5 percent.

Figure 9. - Concluded.

The results of the 1/8-inch (0.32-cm) diameter aperture, full-length (8 in. (20.3 cm)) liner tests, which included configurations with 2.5-, 5-, and 10-percent open areas, as shown in figure 9. The 2.5 percent open-area liner improved the stability of the combustor from about 8 grains (0.52 g) of RDX (unlined combustor) to 28 grains (1.81 g) at a mixture ratio of 2.0. The stability was about the same at a mixture ratio of 1.6; a bomb size of 32 grains (2.08 g) was required to initiate instability as compared with 6 grains (0.39 g) for the bare combustor. The 5- and 10-percent open-area liners could not be pulsed unstable by bombing. Those liners successfully damped pressure disturbances as high as 170 psi (1172 kN/m²) peak to peak (fig. 7) which corresponds to the maximum bomb size of 41 grains (2.66 g). Since the explosive used was in tablet form (fig. 6), the length of the bomb-port limited the bomb size to a maximum of ten tablets or 41 grains (2.66 g).

Spectral analysis of the instability induced using the 2.5-percent open-area liner (fig. 9(b)) shows that the predominant mode is first tangential at both mixture ratios. The oscillograph records show that the predominant mode was first radial (5000 Hz) immediately after bomb initiation, but it shifted to the first-tangential mode (2400 Hz), which had not been noted previously. A possible explanation for the shifting may be that

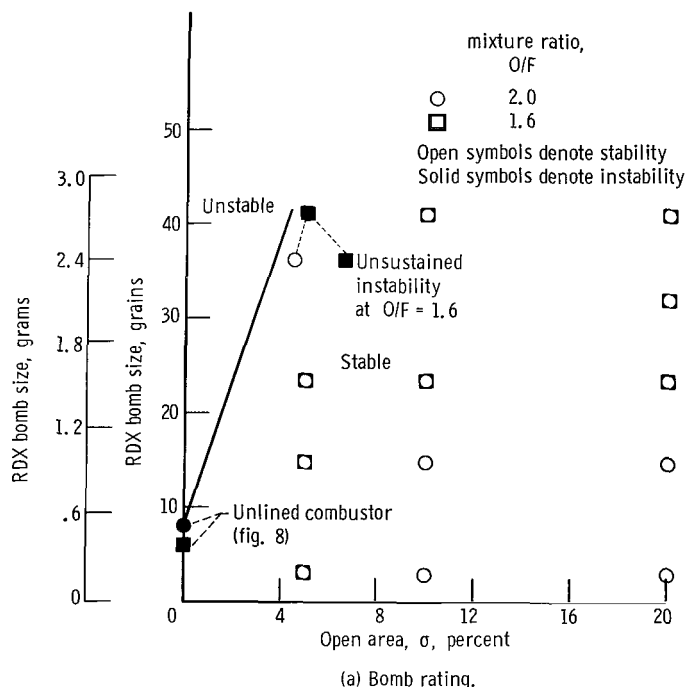
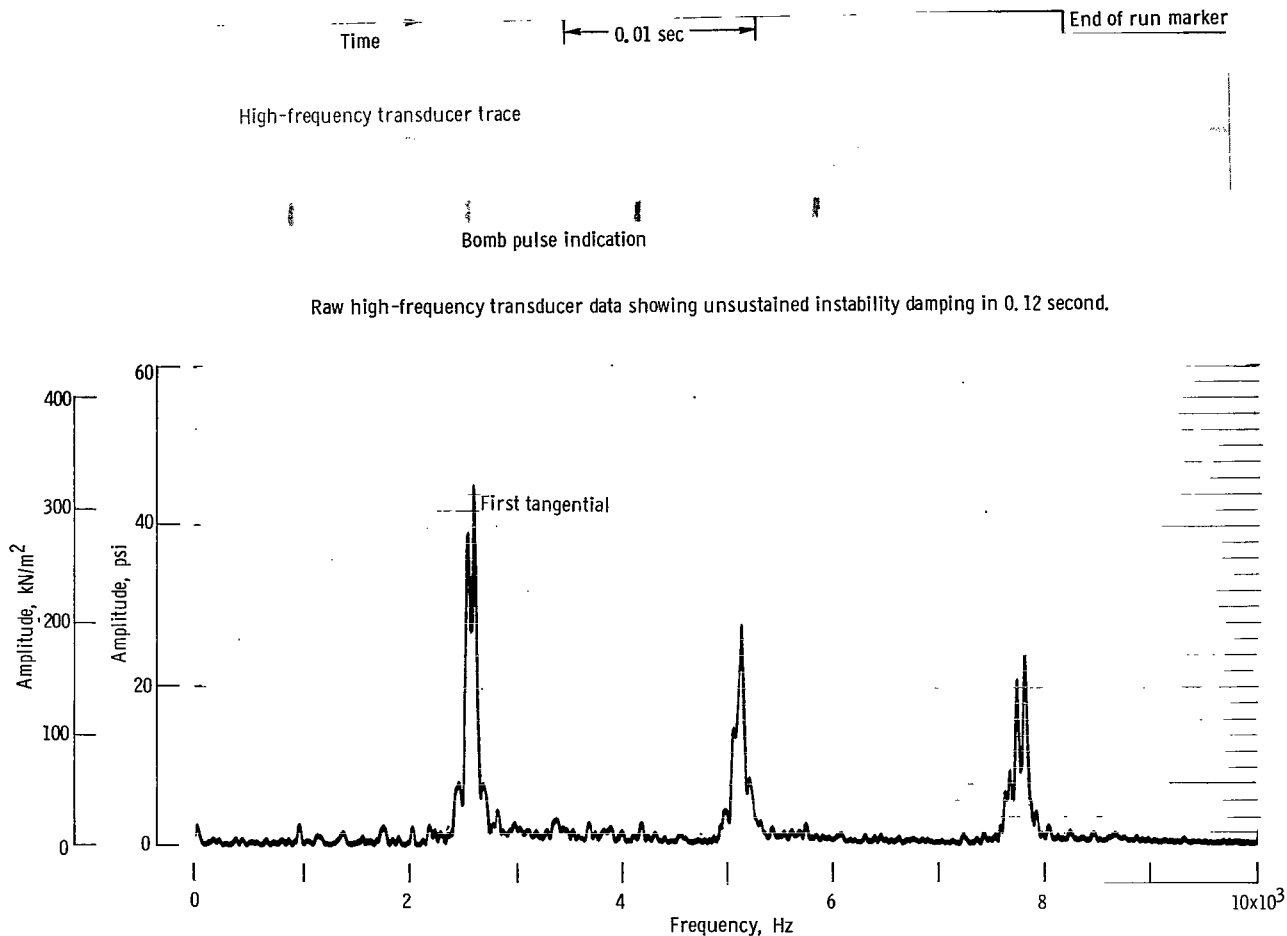


Figure 10. - Effects of experimental percent open area on combustor stability. Aperture diameter, 1/4 inch (0.64 cm); full-length liner, 8 inches (20.3 cm); chamber characteristic length, 42 inches (106.7 cm).



(b) Typical spectral density graph of induced, unsustained instability. Mixture ratio, 1.6; liner open area, 5 percent.

Figure 10. - Concluded.

the high-amplitude wave and increased backing-cavity-gas temperature associated with screech upset the liner damping such that it was ineffective in suppressing the first-tangential mode. Additional discussion is presented in the Theoretical Analysis section.

It must be pointed out that in figure 9(b) and other spectral graphs that follow frequency peaks may be present at multiples of the predominant modes. The phenomena was caused by the spectral analyzer because it produces a Fourier analysis of the data. Analysis of the data in this study was further complicated because liners tend to shift the screech frequency away from the resonant frequency of the liner (ref. 11).

The 1/4-inch (0.64-cm) diameter aperture liners tested were configurations with percent open areas of 5, 10, and 20 percent. As shown in figure 10(a), all 1/4-inch

(0.64-cm) aperture liners, with one exception, successfully damped 41-grain (2.66-g) bombs at either mixture ratio. Instability was initiated with a 41-grain (2.66-g) bomb during one test of the 5-percent open-area liner at an oxidant-fuel ratio of 1.6; however, it was not sustained and damped out within 120 milliseconds. Examination of figure 10(b) shows that the predominant mode was the first-tangential mode (2550 Hz) with apparent Fourier harmonics at 5100 and 7700 hertz. Again, the first-radial mode was predominant immediately after the bomb initiation and modal shifting occurred as previously described.

This series of tests was not conclusive in determining an aperture diameter effect on damping. In the following section significant aperture diameter effects will be noted. It can be concluded, however, that the higher percent open-area liners were very effective suppression devices in that they damp disturbances as high as 170 psi (1172 kN/m²) peak to peak.

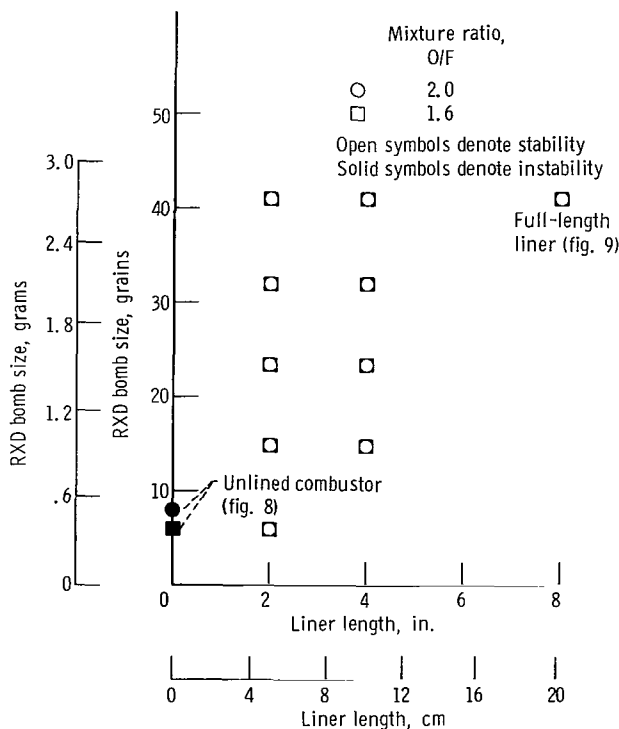


Figure 11. - Effect of experimental liner length on combustor stability. Aperture diameter, 1/8 inch (0.32 cm); open area liner, 10 percent; chamber characteristic length, 42 inches (106.7 cm).

Liner Length Effect in 42-Inch (106.7-Cm) Characteristic-Length Combustor

At present, analytical design equations have no provision to determine the number or location of the resonators required for stabilization. Experiments of reference 5 have determined that full-length combustor liners were not required for complete stabilization using hydrogen-oxygen propellants. Therefore, a series of liners was experimentally evaluated with storable propellants varying the length while other parameters were held constant. The effect of length was evaluated with 10-percent open-area liners and positioned adjacent to the injector. Two aperture diameters of 1/8 and 1/4 inch (0.32 and 0.64 cm) and lengths of 2 and 4 inches (5.1 and 10.2 cm) were tested.

The results of the 1/8-inch (0.32-cm) diameter aperture (10-percent open-area) partial length liner tests are shown in figure 11. Similar to the full-length configuration, these partial length liners successfully damped a bomb size of 41 grains (2.66 g) of RDX at either mixture ratio. The 41-grain (2.66-g) charges produced pulses of from 90 to 170 psi (620 to 1172 kN/m²) peak to peak in these configurations.

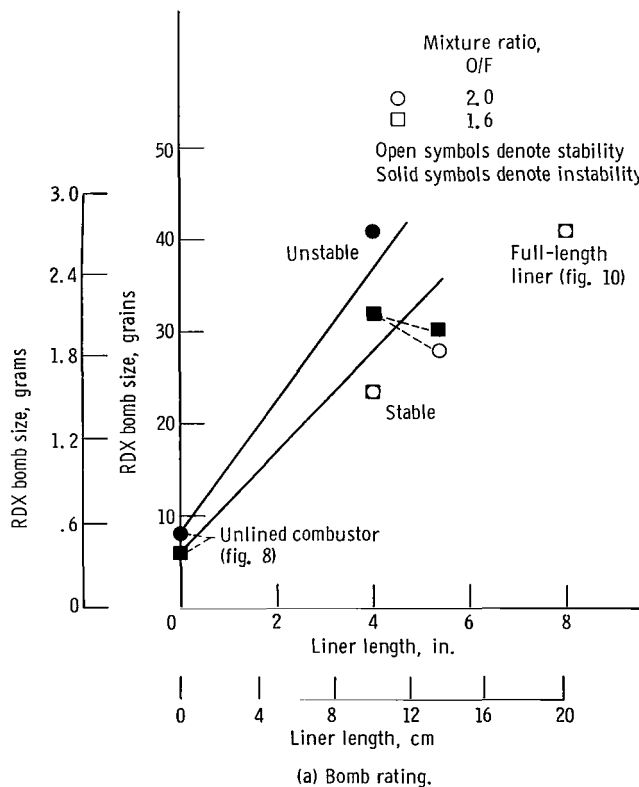
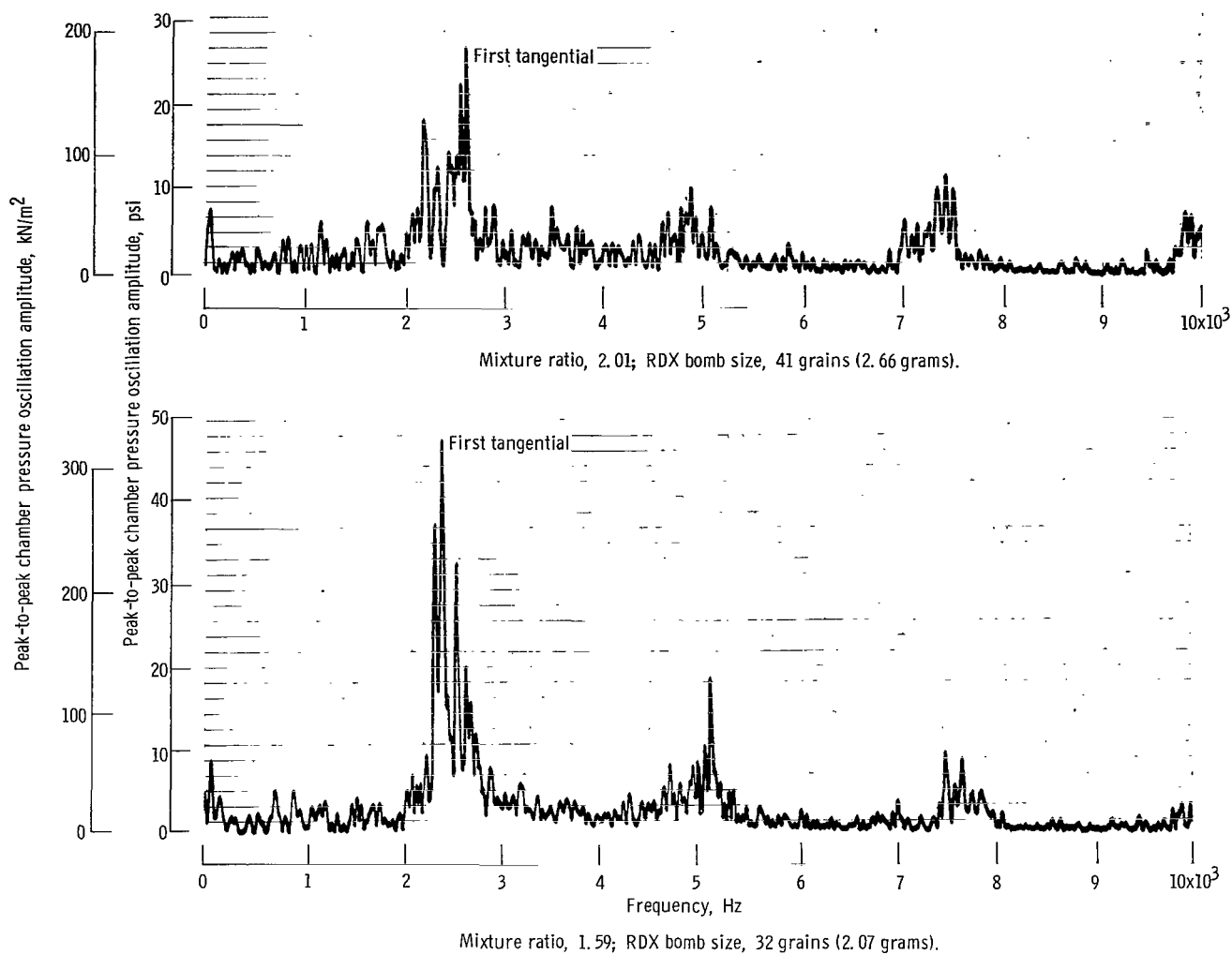


Figure 12. - Effect of experimental liner length on combustor stability. Aperture diameter, 1/4 inch (0.64 cm); liner open area, 10 per cent; chamber characteristic length, 42 inches (106.7 cm).



(b) Typical spectral density graphs of induced instability. Liner length, 4 inches (10.2 cm) or one-half full length.

Figure 12. - Concluded.

The results of the 1/4-inch (0.64-cm) diameter aperture (10-percent open-area) tests can be seen in figure 12(a). The half-length (4 in. or 10.2 cm) liner was driven into the first-tangential mode (fig. 12(b)) with 32 and 41 grains (2.08 and 2.66 g) of RDX at mixture ratios of 1.6 and 2.0, respectively, as compared with the full-length 1/4-inch (0.64-cm) diameter aperture liner, which was stable up to 41 grains (2.66 g). Although the combustor was pulsed unstable, the liner improved the stability considerably; that is, a larger bomb was required to induce instability with a lined chamber than with an unlined chamber.

It can be concluded that, with storable propellants as well as hydrogen-oxygen (ref. 5), full-length liners were not required for screech suppression in the combustors

used in these studies. It is also apparent from these tests that the 1/4-inch (0.64-cm) diameter aperture liner is less stable to bomb pulses than the 1/8-inch (0.32-cm) diameter aperture liner. Therefore, the length of the liner required was dependent on the absorbing qualities of the liner.

Effect of Percent Open Area and Aperture Diameter on Liner Backing-Cavity-Gas Temperature

An important design condition for acoustic liner peak performance is tuning the resonator cavity to the screech frequency. (Ref. 11 shows the importance of tuning to pre-transition oscillations with hydrogen-oxygen propellants.) Tuning is directly affected by sonic velocity of the gas in the backing cavity (see eq. (1)). Therefore, careful consideration must be given to the properties of the liner backing-cavity gas. The composition of this gas, in general, was assumed to be combustion products (no gas samples were taken). However, predicting the temperature of the gas is difficult. Variations in liner percent open area and recirculation patterns caused by changes in injector thrust per element, element radial location, and propellant combination would be expected to affect the gas temperature. To gain information relating these temperatures with engine variables and to allow analysis of results obtained, thermocouples were installed to measure the gas temperature during these tests. When data taken during stable, steady-state combustion ($L^* = 42$ in. (106.7 cm)) were used, backing-cavity-gas properties were determined and used for theoretical analysis.

Figure 13 shows the temperature extremes (shown by the bars) measured in the backing cavity during steady-state operation. The data points are averages of the temperatures measured for each percent open area at the end of the run. The gas temperatures increase rapidly with percent open area up to 20 percent where they seem to level off. The temperature increase from 2.5 to 10 percent is nearly linear, 1750° to about 2450° R (972° to 1362° K), but the average temperature at 20-percent open area is 2740° R (1522° K) which corresponds to an increase of 290° R (161° K) compared with 700° R (389° K) for the initial 7.5-percent increment. The 20-percent open-area backing-cavity-gas temperature compares well with unpublished boundary-layer-temperature data (2800° to 3000° R) (1556° to 1667° K) taken with a similar injector and combustion chamber without a liner (theoretical bulk combustion gas temperature was about 5300° R (2945° K)). As open area increases, apparently more and more of the combustor boundary-layer gas enters the resonator, thereby raising the backing-cavity-gas temperature. It may be hypothesized that a high percent open-area liner (20 percent or more) for storable-propellant rockets can possibly be designed fairly accurately with regard to backing-cavity-gas temperature, if the combustor boundary-layer temperature is

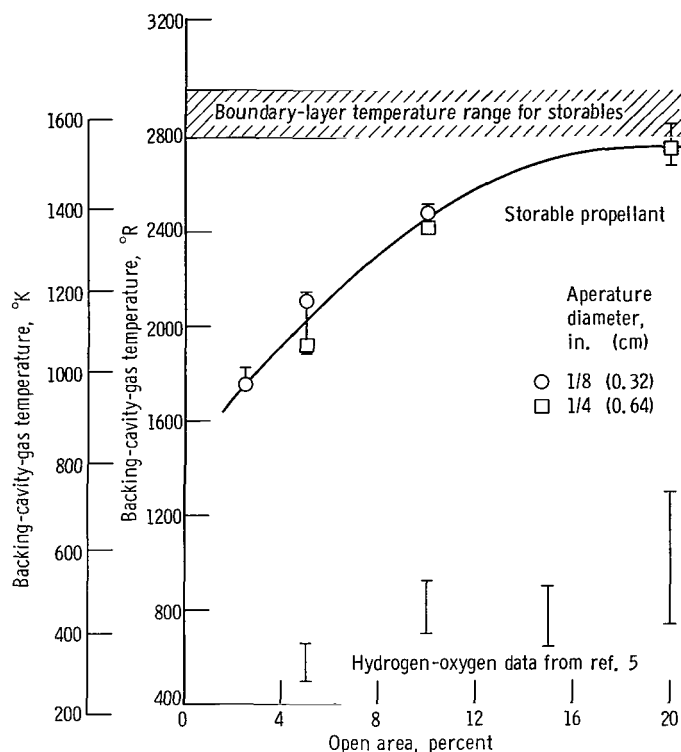


Figure 13. - Effect of percent open area on liner backing-cavity-gas temperature during steady-state stable operation. Chamber characteristic length, 42 inches (106.7 cm); nominal mixture ratio, 2.0. Average temperatures, denoted by symbols, were used for theoretical calculations.

known. The boundary-layer gas temperature could be determined with a simple injector-combustor test by installing thermocouples or calorimeters in the combustion-chamber wall for the measurement. This would eliminate the initial tests now required with liner installation for determining the backing-cavity-gas temperatures.

The effect of propellant combination on backing-cavity temperature can be seen in figure 13. The hydrogen-oxygen backing-cavity-temperature data from reference 5 are plotted with the storable propellant data. It can be seen that the storable-propellant backing-cavity-gas temperatures are about 1400°R (778°K) higher than the hydrogen-oxygen data. This was probably because of the hydrogen-oxygen injector design which used concentric tube elements. In such a design, oxygen is injected from the inner tube and the colder hydrogen from the outer tube. Obviously, backing-cavity-gas temperature assumptions used to design a liner for one propellant combination cannot be used indiscriminately.

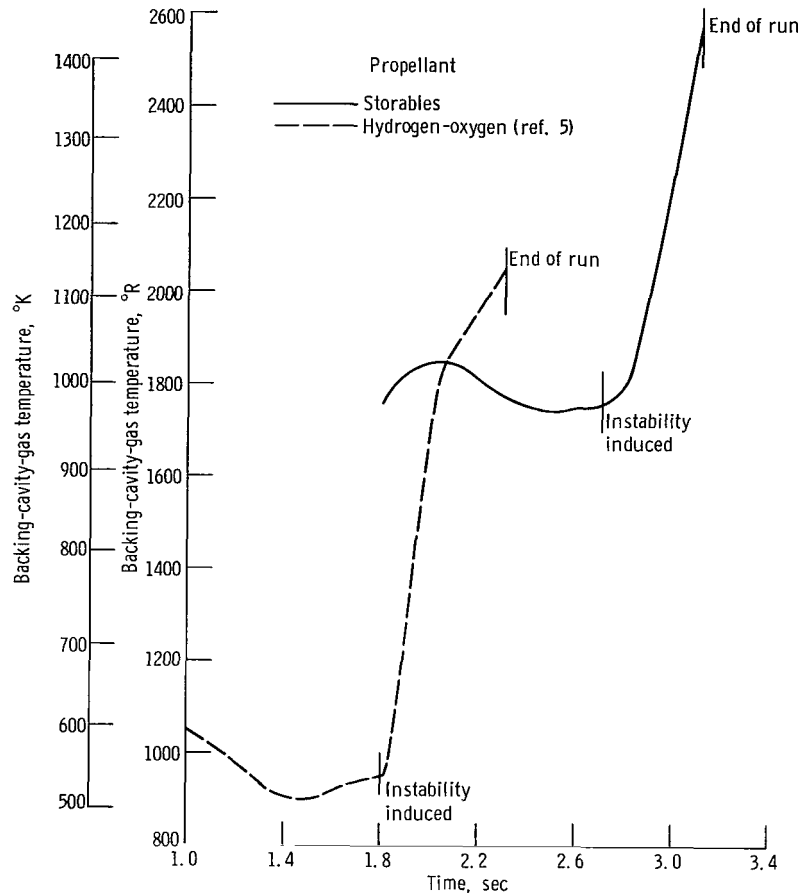


Figure 14. - Comparison of backing-cavity-gas temperature of storable and hydrogen-oxygen propellant combinations during tests when instabilities were encountered.

During tests, when the combustor reached stable, steady-state operation and was then bombed unstable, increases in backing-cavity-gas temperature were on the order of 500° to 800° R (278° to 444° K). These temperature increases were somewhat lower than the hydrogen-oxygen data (fig. 14) which had an increase of about 1000° R (556° K). The temperature usually continued to increase at shutdown with the storables. This may have been a result of the mixture ratio variations during shutdown. These temperature increases only illustrate the detuning effect on the cavity properties during instability; the prescreech backing-cavity-gas properties are used for liner design.

Stability Characteristics of 56-Inch (142.2-Cm) Characteristic- Length Combustor Without Liner

For a severe test, each configuration rated by bombing was also tested in a combustor which was spontaneously unstable without a liner. Spontaneously unstable combustion was created by removing the bomb ring and replacing it with a 10-inch (25.4-cm) cylindrical section with the same injector. Apparently, the additional length caused an initial disturbance which, in turn, immediately initiated the predominant mode. The spectral density analysis (fig. 15(a)) shows that the predominant mode was also first radial (5000 Hz), as in the case of the $L^* = 42$ -inch (106.7-cm) combustor without a liner, at a mixture ratio of 2.0. The modes in the vicinity of 7000 hertz (fig. 15(b)) are not as well defined as they were in the case of the $L^* = 42$ -inch (106.7-cm) combustor and could be fourth tangential, first tangential and first radial combined, or some other complex mode.

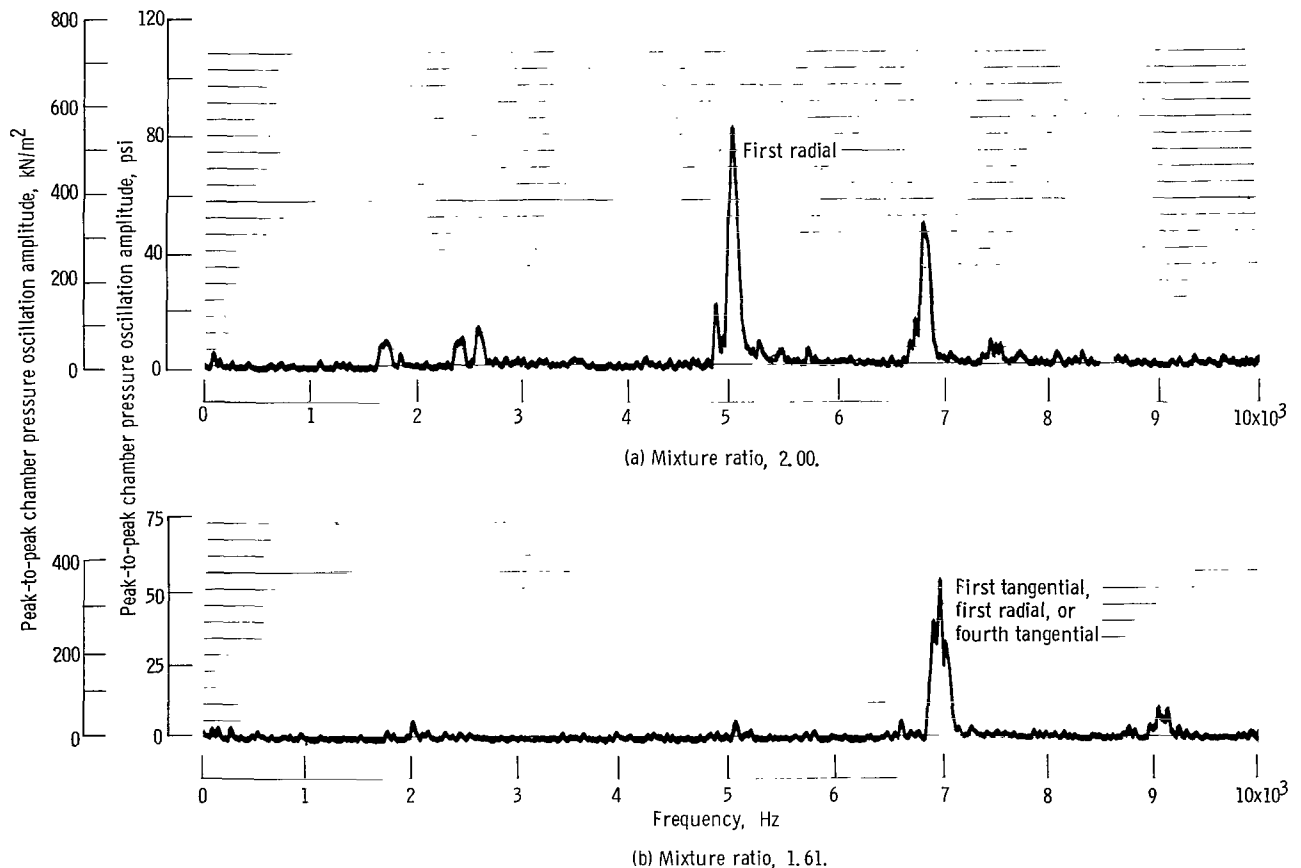


Figure 15. - Stability characteristics of unlined spontaneously unstable, combustor. Chamber characteristic length, 56 inches (142.2 cm).



Aperture Diameter and Liner Percent Open Area Effect in 56-Inch (142.2-Cm) Characteristic-Length Combustor

The series of apertures and percent open areas (full-length liners) that was tested in the spontaneously unstable combustor was the same as the series that was bomb rated in the shorter ($L^* = 42$ -in. or 106.7-cm) chamber. The results of these tests are summarized in table II. As shown in figure 16(a), the amplitude of first-radial mode (from fig. 15(a)) was depressed by the 1/8-inch (0.32-cm), 5-percent open-area liner, but other modes in addition to the first and second longitudinal appeared at 2900, 8050, and 8850 hertz. The first-longitudinal modes present during these test cannot be expected to be damped because the liners were designed to be tuned for higher frequency (2500 to 5000 Hz) modes. Also, the length (30.5 in. or 77.5 cm) makes the combustor very sus-

TABLE II. - APERTURE DIAMETER AND OPEN AREA RATIO
EFFECTS IN 56-INCH CHARACTERISTIC CHAMBER
LENGTH COMBUSTOR

[Liner thickness, 3/16 in. (0.48 cm); liner backing-cavity
height, 1 in. (2.54 cm); oxidant-fuel ratio, 2.0.]

Aperture diameter		Open area, percent	Stability characteristics		Figure
in.	cm		Predominant mode	Secondary mode	
1/8	0.32	5	Second longitudinal	Higher modes also present at lower amplitudes	16(a)
		10	First longitudinal	Multiples of first-longitudinal mode present ^a	16(b)
1/4	0.64	5	First transverse	-----	17(a)
		10	First longitudinal	Multiples of first-longitudinal mode present ^a	17(b)
		20	First longitudinal	Second longitudinal present at lower amplitudes	17(c)

^aFirst-longitudinal mode multiples may be produced by spectral analyzer.

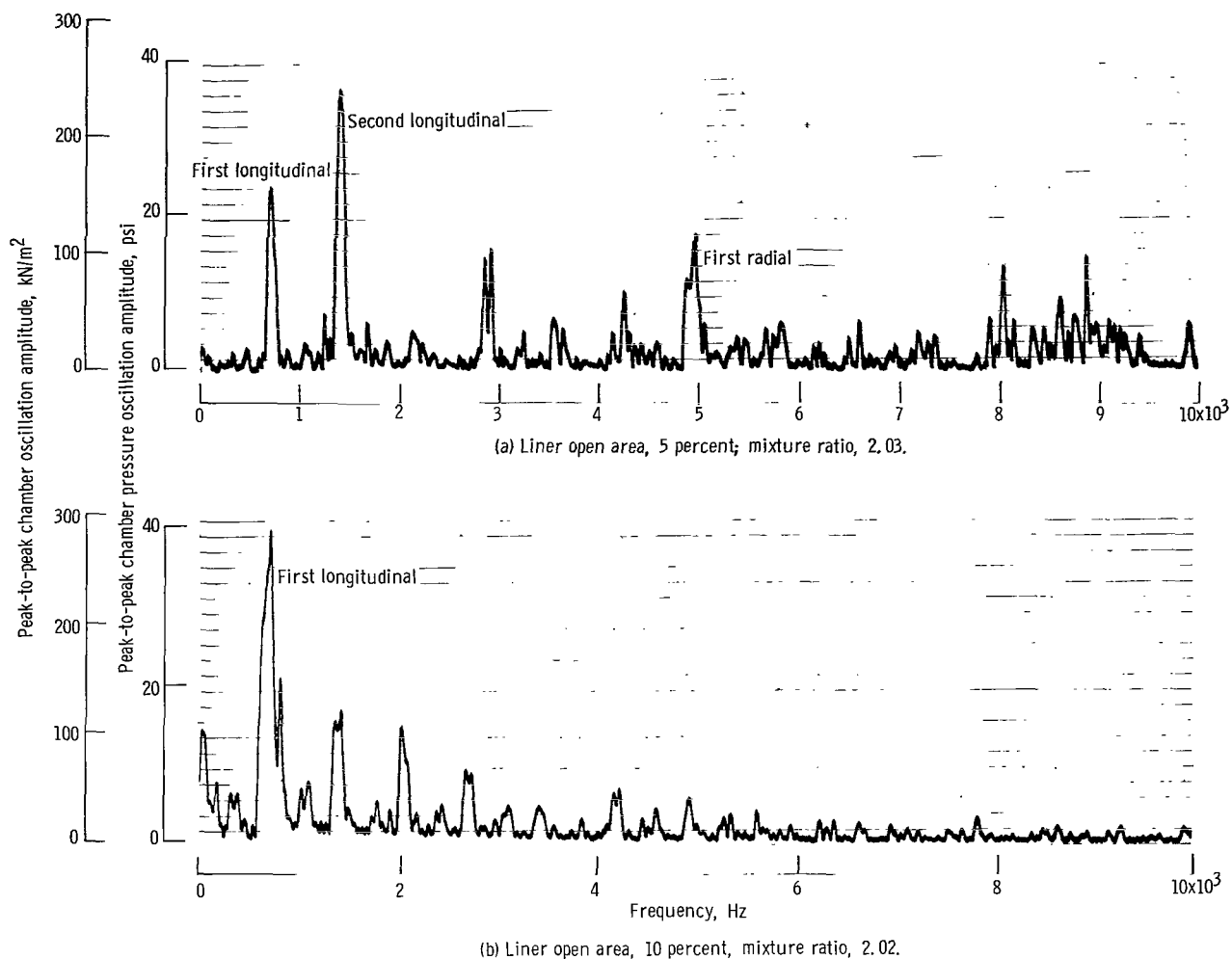


Figure 16. - Typical spectral density graphs of instability encountered during tests of 1/8 inch (0.32 cm) diameter aperture, full length liners. Chamber characteristic length, 56 inches (142.2 cm).

ceptible to longitudinal modes. These reasons, along with the conclusion from reference 12 that the energy in the combustor will distribute itself into modes with least damping, explain the presence of the undamped longitudinal mode. The 1/8-inch (0.32-cm), 10-percent open-area liner damped the transverse modes completely, but the first-longitudinal mode was not damped, figure 16(b).

Typical spectral analyses of the combustion oscillations in the presence of the 1/4-inch (0.54-cm) diameter aperture liners are shown in figure 17. The 5-percent open-area liner depressed the amplitude of the first-radial mode, but the first-tangential mode became predominant (fig. 17(a)). It should be noted that the peak corresponding to the first-radial mode (5000 Hz) may be a Fourier harmonic produced by the analyzer since the peaks occur at multiples of the first-tangential mode. The same may be true for the analysis of the 10-percent open-area liner (fig. 17(b)). The predominant mode is the

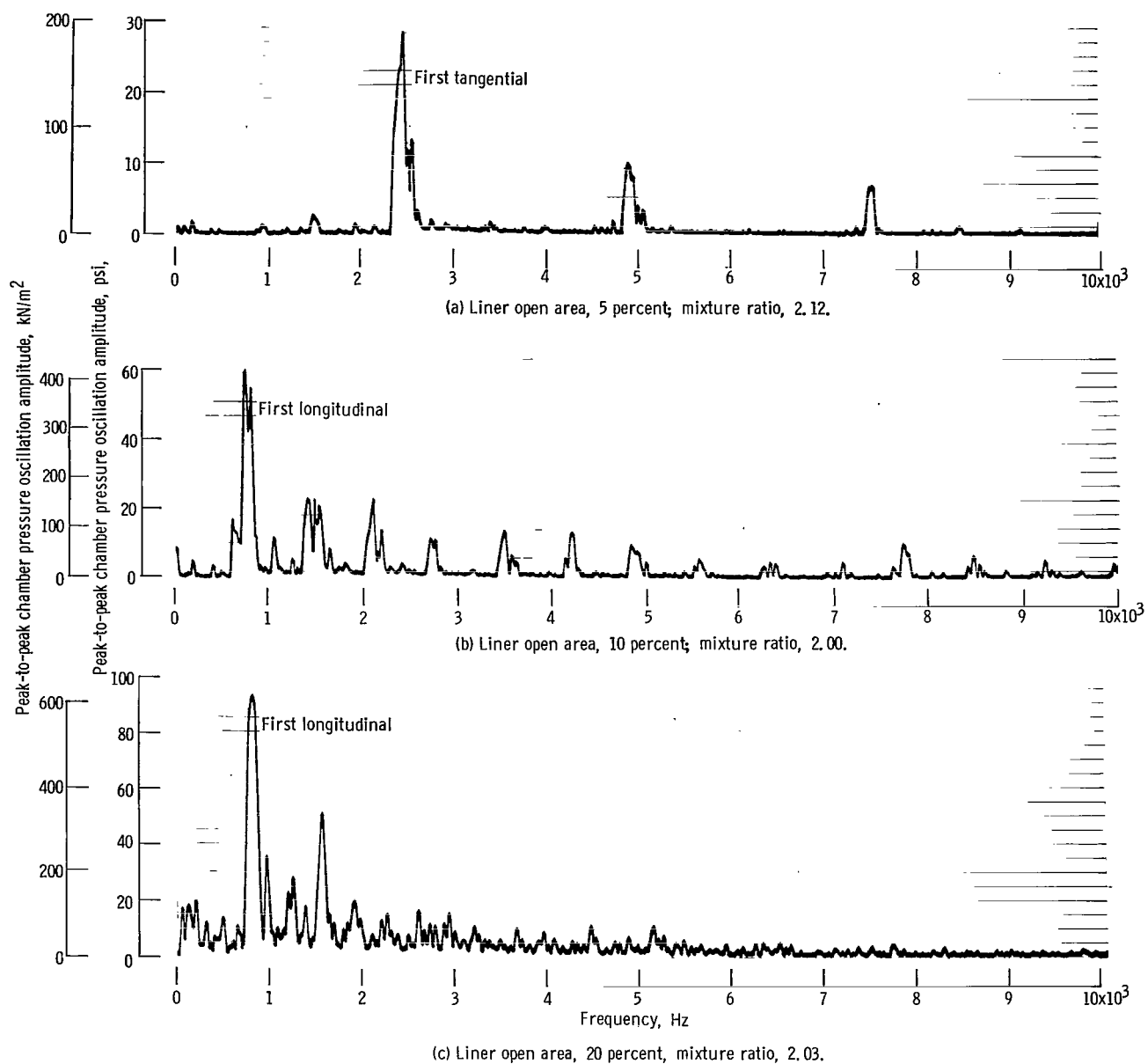


Figure 17. - Typical spectral density graphs of instability encountered during tests of 1/4-inch (0.64-cm) diameter aperture, full length liners. Chamber characteristic length, 56 inches (142.2 cm).

first longitudinal but several other peaks can be noted at even intervals. It appears that the 20-percent open-area liner damped the transverse modes (fig. 17(c)), but again the first-longitudinal mode remained. It was also noted that no Fourier harmonics are present in figure 17(c), so some of the peaks in figure 17(b) may have actually been screech modes.

In summary, it was noted that damping increased as percent open area increased. Also, the liners would not damp the first-longitudinal mode (700 Hz) because the frequency was below the intended range. In both the 1/8- and 1/4-inch (0.32- and 0.64-cm) apertures, 5-percent open-area tests, the liners did not completely damp the transverse modes as seen in figures 16(a) and 17(a), whereas, the 10- and 20-percent, open-area liners generally did suppress the transverse modes. It should also be pointed out in comparing these figures that the 1/8-inch (0.32-cm) aperture liner (fig. 16(a)) displayed somewhat better absorption than did the 1/4-inch (0.64-cm) aperture liner (fig. 17(a)). The predominant modes were the first tangential with the 1/4-inch (0.64-cm) aperture liner and the second longitudinal with the 1/8-inch (0.32-cm) aperture liner. These data agree with the $L^* = 42$ inch (106.7-cm) liner length effect data in that the 1/8-inch (0.32-cm) apertures were an improvement over the 1/4-inch (0.64-cm) aperture liners. The conclusion remains, however, that liners that were completely effective in the shorter (42-in. (106.7-cm) L^*) chamber allowed screech modes at frequencies remote from the design frequency to persist in the longer (56-in. (142.2-cm) L^*) thrust chamber.

The $L^* = 56$ -inch (142.2-cm) combustors were not bombed even though a liner would partially stabilize the combustion process. The increased heat transfer created by the longitudinal instability destroyed the bombs before they could be detonated.

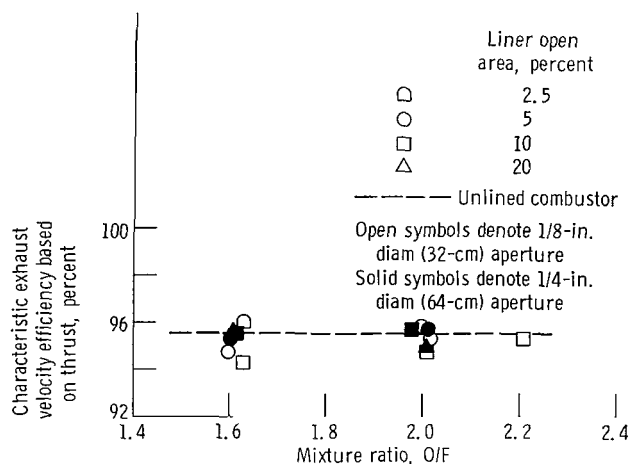


Figure 18. - Effect of liners on characteristic exhaust velocity efficiency in combustor. Stable combustion; chamber characteristic length, 42 inches (106.7 cm).

Liner Effect on Characteristic Exhaust Velocity Efficiency

Liners had no significant effect on C^* efficiency, as shown in figure 18. Efficiencies presented are only for the 42-inch (106.7-cm) L^* stably operating combustor. Data for the 56-inch (142.2-cm) L^* testing was not plotted because of the presence of the first-longitudinal mode during all tests.

Theoretical Analysis of Circular Aperture Liner Data

The previous sections were primarily concerned with the experimental results of the various liner configurations tested. The following discussion will be concerned with applying Helmholtz resonator theory to the results. A series of calculations using this theory was performed to obtain values of the liner resonant frequency and the absorption coefficient for comparison with experimental results. The first consideration for an effective liner design is to match the liner resonant frequency to the screech frequency (or the pretransition oscillation frequency of ref. 11), that is, to tune the liner. However, the problems encountered using acoustic theory for liner analysis are knowledge of (1) backing-cavity-gas composition, (2) amplitude of the pressure oscillations, and (3) the flow past or through the apertures. The backing-cavity-gas composition and temperature must be known to compute the resonant frequency of the liner. The amplitude of the oscillations affect nonlinear factors, and flow past or through the apertures results in a shift in the resonant frequency of the liner.

Gas temperatures measured in the cavity and composition of the combustion products (based on theoretical thermodynamic calculations similar to those in ref. 13 because gas samples were not taken) were used in the analysis. An arbitrary value of 26 psi (179 kN/m²) peak-to-peak (190 dB) was assumed as the amplitude of the triggering disturbance (combustion noise) for the spontaneously unstable combustors. A value of 100 psi (6.89 kN/m²) peak-to-peak (199 dB) was assumed for the bomb pulsed combustors. The predominant frequency of the combustion noise was assumed to be the same as the induced instability which was 5000 hertz at a mixture ratio of 2.0. The prescreech oscillation or combustion noise distributes itself into the normal chamber modes, and the highest amplitude occurs at the mode where the least chamber damping exists (ref. 12). The liners were designed, therefore, to damp the oscillation which can grow into screech.

Before the absorption coefficients of a liner can be calculated, it is necessary to determine its resonant frequency. If the composition and the temperature of the backing-cavity-gas are known, the resonant frequency can be readily determined using equation (1) for the case of no flow past or through the apertures.

$$\left(f_o = \frac{12c}{2\pi} \sqrt{\frac{\sigma}{Ll_{\text{eff}}}} \right) \quad (1)$$

where

$$l_{\text{eff}} = t + 0.85 d(1 - 0.7\sqrt{\sigma})$$

(Symbols are defined in the appendix.) The problem, however, is to account for the effect of flow past or through the apertures on resonant frequency. Investigations reported in references 15 and 16 have developed an empirical relation for the shift in resonant frequency $\Delta f_o/f_o$ as a function of flow past the apertures (using air). Using this relation, the resonant frequency is modified as follows:

$$f_{\text{ov}} = f_o \left(1 + \frac{\Delta f_o}{f_o} \right) \quad (2)$$

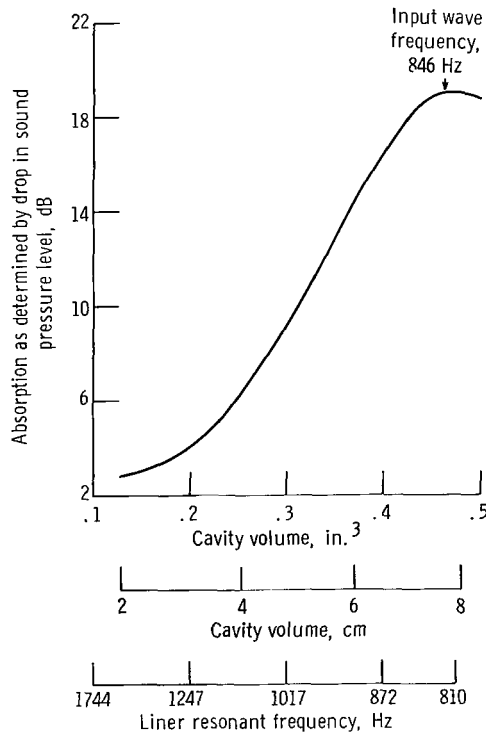


Figure 19. - Effect on damping of tuning liner to screech frequency. (Data from ref. 12).



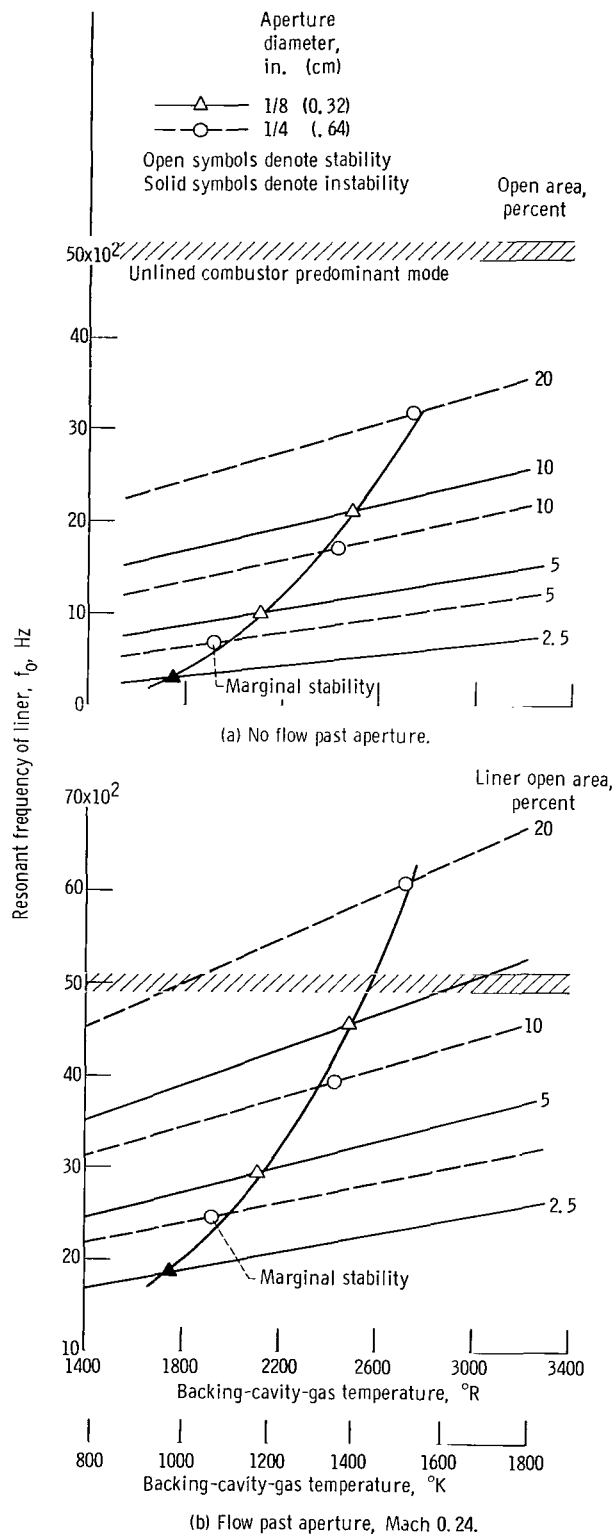


Figure 20. - Calculated resonant frequencies of full length liners tested as function of backing-cavity-gas temperature.

To extrapolate these results to media other than air, it appears from the results of reference 5 that the shift in frequency is related to the free-stream Mach number. Hence, a flow past the aperture of Mach 0.24 was chosen in line with the findings in reference 5. This flow corresponded to a frequency shift $\Delta f_o/f_o$ of 0.50 (ref. 15).

According to references 8, 12, and 14, the liner absorption is at a maximum when the liner resonant frequency is equal to the screech frequency (the assumed predominant chamber mode), that is, tuned. Figure 19, the cold-flow test results from reference 12, shows that the highest drop in sound-pressure level of screech occurs about when the liner resonant frequency matches the input-wave frequency (resonant frequency was varied by changing the backing-cavity volume). Tuning can be used then to characterize the damping of a liner. The calculated resonant frequencies of the various liners tested are compared with the screech frequency in figure 20(a) (without flow), and in figure 20(b) (with flow). It can be seen from the figures that the liners whose resonant frequencies were nearest the screech frequency (5000 Hz) absorbed best and that liners with resonant frequencies below 2500 hertz (flow shifted) were not completely successful. The 1/8-inch (0.32-cm) diameter aperture liners all had higher resonant frequencies than 1/4-inch (0.64-cm) diameter aperture liners because (1) the effective length l_{eff} was lower and (2) the sonic velocity was higher since the average backing-cavity-gas temperature was slightly higher. Since both analyses (i.e., with or without flow past) compare favorably with trends exhibited by the experimental data, it is impossible to check the validity of the flow past model.

Even though tuning is necessary for high damping, a liner with a resonant frequency near the screech frequency does not necessarily mean that it will damp that frequency once the combustor is unstable. For example, the 1/8-inch (0.32-cm), 2.5-percent open-area and the 1/4-inch (0.64-cm), 5-percent open-area liners allowed screech in the first-tangential mode (figs. 9(b) and 10(b)). As seen in figure 20, the resonant frequencies are near 2400 hertz which corresponds to the first-tangential mode. It was noted, from the high-frequency transducer oscillograph records, that the frequency immediately after the inception of screech was about 5000 hertz (first-radial mode), but it then shifted to 2400 hertz (first-tangential mode). As stated in the experimental results discussion, apparently the liner damping was adversely affected by the high-amplitude screech waves and the increased backing-cavity-gas temperature associated with screech. Reference 12 states that the energy in a combustor will distribute itself into modes with the least damping. Therefore, it seems that the liners were affected by the screech in such a way that damping was lowest for the first-tangential mode after the inception of screech.

The next step in the theoretical analysis was to calculate absorption coefficients for the liners. Absorption coefficient, α , is defined as the percent of total incident energy damped by the liner and is shown in the following equation:

$$\alpha = \frac{4\theta}{(\theta + 1)^2 + X^2} \quad (3)$$

where

$$\theta = \frac{2(2\mu\rho\omega)^{1/2}}{\sigma\rho c} \left(1 + \frac{\Delta_{nl}}{d} + \frac{t}{d} \right) \quad (4)$$

and

$$X = \frac{\omega_o l_{eff}}{12c\sigma} \left(\frac{f}{f_o} - \frac{f_o}{f} \right) \quad (5)$$

The effect of tuning can also be seen in equation (3). As acoustic reactance X approaches zero, tuning absorption α increases. The calculated absorption coefficients are somewhat questionable, however, because of discrepancies among investigations in the empirical relations used in the calculation. The values for Δ_{nl}/d (used in eq. (4)) were obtained from reference 14, and used directly in the calculation of absorption coefficient. It must be noted, however, that direct application of the data of reference 14 without accounting for change in viscosity and frequency (according to ref. 17) may be in error.

Figure 21(a) is presented as a summary plot of liner performance. The plot shows the relation between absorption coefficient and the minimum bomb size required to induce instability (assuming no flow past the apertures). The 56-inch (142.2-cm) L^* combustor data are presented as zero grains (or grams) of explosive. The calculated absorption coefficients agree well with the data presented earlier where it was found that stability increased as percent open area was increased. Also, the 1/4-inch (0.64-cm) aperture calculated absorption coefficients are lower than the calculated absorptions of the 1/8-inch (0.32-cm) aperture liners with the same percent open areas, which agrees with the experimental data.

It can be seen that a minimum of about 10-percent absorption was required for stabilization using this analysis, which is the same for both combustor lengths.

Presented in figure 21(b) are the calculated absorption coefficients assuming a flow past the apertures of Mach 0.24. This assumed flow raised the calculated absorption coefficients, but the percent open area and aperture diameter correlations were the same as the zero flow case with the exception of the 1/4-inch (0.64-cm) diameter, 10- and 20-percent open-area liners used in the 56-inch (142.2-cm) L^* combustor. The 42-inch (106.7-cm) L^* combustor required a minimum absorption coefficient of about 45 percent, whereas the 56-inch (142.2-cm) L^* combustor required about 65 percent with this

analysis. Neither analysis agreed with the 25-percent minimum absorption quoted from reference 5 for hydrogen-oxygen propellants. This disagreement could be a result of the differences in chemical reactions of the two propellant combustions, different thrust-per-element, or in the analysis itself. A flow assumption corresponding to Mach 0.11 was required for correlation at a minimum absorption of 25 percent. There is no justification for using Mach 0.11, whereas Mach 0.24 is an approximate average free-stream Mach number at the liner. The flow shift of reference 14 is based on the free-stream Mach number. However, there is no definite proof that free-stream Mach number controls the shift.

When the previous theoretical analysis and the experimental information gained is used, a liner design procedure can be proposed. Knowing the combustor frequency f_o and using an average free-stream Mach number over the liner, a flow past frequency shift can be calculated $[1 + (\Delta f_o/f_o)]$ using reference 15. And using the flow past shift, calculate a required resonator frequency $f_{ov} = f_o[1 + (\Delta f_o/f_o)]$. Using equation (1), the backing-cavity height or percent open area required for tuning can be calculated. Also, the required volume per aperture for tuning can be calculated using equation (1) modified as

$$f_{ov} = \frac{C}{2\pi} \sqrt{\frac{S}{V l_{eff}}}$$

where

$$\frac{\sigma}{L} = \frac{S}{V}$$

(ref. 12) and where S is aperture area, V is resonator volume per aperture, and $l_{eff} = t + 0.85 d(1 - 0.7\sqrt{\sigma})$. The values chosen for t , d , σ , and S will necessarily be a compromise in an actual engine due to space, strength, and cooling requirements. The sonic velocity of the resonator gas c is very critical, and care should be taken in its calculation. Further qualitative analysis using equation (3) can be made, however, as stated previously, tuning is the first consideration in the design of a successful liner.

Since the liners tested in the 56-inch (142.2-cm) L^* combustor did not suppress the first-longitudinal mode (700 Hz), a preliminary analysis was made to determine a design that could be used to suppress that mode. The results of the analysis indicated that, for tuning and sufficiently high absorption coefficient (more than 60 percent, see fig. 23), a liner on the order of the following dimension would be needed: 1/4-inch (0.64-cm) diameter apertures, 5-percent open area, 1.0-inch (2.54-cm) thick, and 2.0-inch (5.08-cm) backing-cavity depth. To assure stable combustion in the 56-inch (142.2-cm) L^* com-

bustor, a combination of two liners in series would be required to provide damping over a wide frequency bandwidth, that is, 700 to more than 5000 hertz. Probably, a more effective position for the first-longitudinal mode damper would be downstream of the high-frequency damper and near the longitudinal antinodal point.

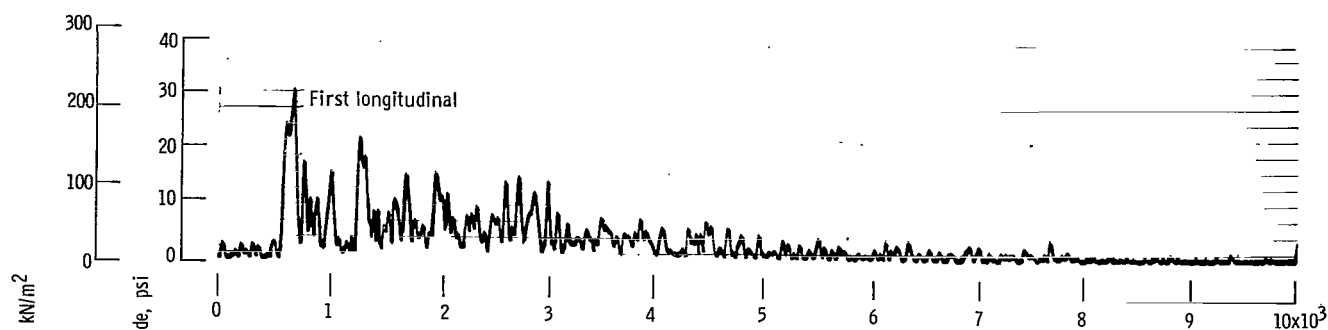
Aperture Shape Effects

Van Itterbeek indicated in reference 18 that aperture shape had a significant effect on absorption. The results showed that the aperture perimeter to cross-sectional area ratio P/A affected the absorption; that is, the aperture with the largest P/A absorbed best. Accordingly, in this study, P/A was increased by using slits, crosses, and slots rather

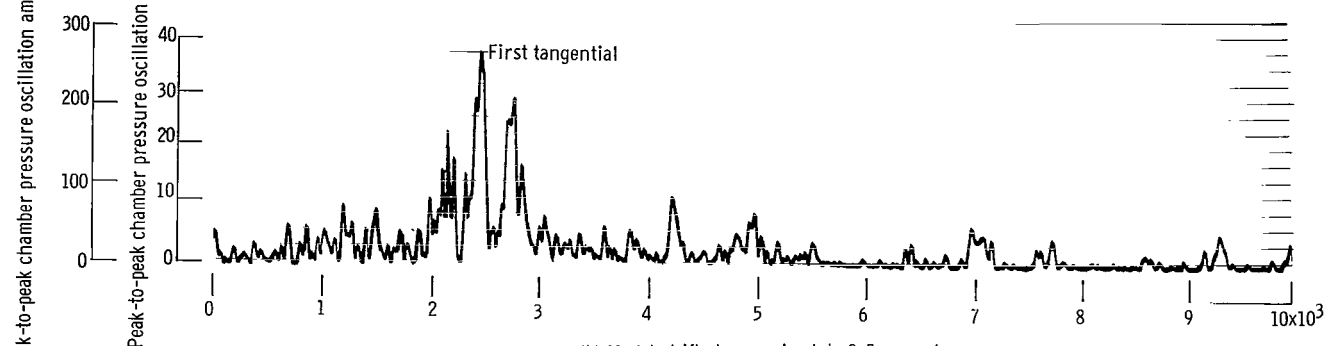
TABLE III. - APERTURE SHAPE EFFECTS

[Liner thickness, 3/16 in. (0.4763 cm); liner backing-cavity height, 1 in. (2.54 cm); liner length, 8 in. (20.32 cm); oxidant-fuel ratio, 2.0.]

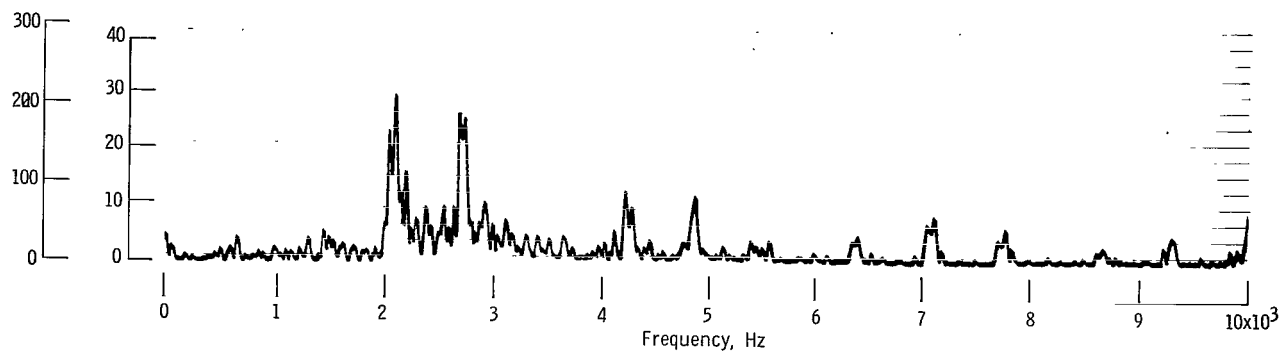
Chamber characteristic length, L*		Aperture geometry	Open area, percent	Aperture dimensions				Aperture perimeter to cross-sectional area ratio, P/A		Stability characteristics	Figure
				Length		Width					
in.	cm			in.	cm	in.	cm	in. ⁻¹	cm ⁻¹		
56	142.2	Longitudinal slots	5	7½	19.05	1/16	0.16	33.8	85.9	Frequencies shifted during run; first-longitudinal to second-tangential modes to 2100 Hz	22
			11	7½	19.05	1/8	0.32	17.2	43.7	Second-longitudinal mode predominant with higher frequencies	23(a)
			16.5	7½	19.05	3/16	0.48	11.6	29.6	First-longitudinal mode predominant	23(b)
		Cross	10	1/4	0.64	1/8	0.32	10.0	25.4	First-longitudinal mode predominant; other higher modes also present	25(a)
			10	13/16	2.06	1/32	0.08	31.8	80.8	First longitudinal mode predominant	25(b)
42	106.7	Longitudinal slots	5	7½	19.05	1/16	0.16	33.8	85.9	All bombs damped at 41-grain (2.66-g) maximum bomb size	----
		Alternating slits	10	13/32	1.03	1/16	0.16	38.3	97.3	All bombs damped except one, 41-grain (2.66-g) bomb at oxidant-fuel ratio of 1.6; first-tangential mode damped after 0.18 sec	26



(a) Screech encountered as combustor reached steady-state operation at time zero.



(b) Modal shift at approximately 0.5 second.



(c) Modal shift immediately before shutdown at approximately 1.0 second.

Figure 22. - Typical spectral density graph of instability encountered in combustor. Width of axial-slot liner, 1/16 inch (0.16 cm); liner open area, 5 percent; chamber characteristic length, 56 inches (142.2 cm); mixture ratio, 1.99.

than circular apertures. Although in a regeneratively cooled rocket engine the crosses and alternating slits would probably be impractical, they might be used in an ablative, radiation cooled or possibly a ceramic type engine. The longitudinal slots could be used readily in a regeneratively cooled engine; gaps could be formed between the longitudinal cooling tubes.

Although, only a small amount of data are available for theoretical analysis of the various shapes, a series of experimental tests were made using liners with crosses, longitudinal slots, and alternating slits. Figures 4(b) and (c) are photographs of a slot and a cross liner, respectively. Because of bomb rating problems in the circular aperture program (i.e., the maximum bomb size limitation prevented extension rating of the liners), all the liners were tested in the 56-inch (142.2-cm) L* combustor. Two bomb-tests were made in the 42-inch (106.7-cm) L* combustor for comparison and to obtain backing-cavity-gas temperatures. The aperture shape tests are summarized in table III.

Longitudinal slot aperture tests in 56-inch (142.2-cm) characteristic length combustor. - A series of tests were made using longitudinal slot liners to simulate gaps to be used between cooling tubes in regenerative engines. Full-length, $7\frac{1}{2}$ -inch (19.05 cm) longitudinal slots 1/16, 1/8, and 3/16 inch (0.16, 0.32, and 0.48 cm) wide were tested. The corresponding open area ratios were 5, 11, and 16.5 percent. Spectral density graphs of the instability observed using the 1/16-inch (0.16-cm), 5-percent open-area liner are shown in figure 22. Figure 22(a) shows a predominant first-longitudinal mode early in the run; figure 22(b) shows the mode shifting to an apparent first-transverse mode 0.5 second later; and figure 22(c) shows what appears to be a shifted first-transverse - third-longitudinal mode just before shutdown. A problem arises in defining the mode near 2100 or 2200 hertz, because it is near a longitudinal multiple, third-longitudinal mode. Modal peak shifting was probably a result of changing backing-cavity-gas temperature (tuning) and a low or marginal absorption coefficient.

Figure 23(a) shows the screech encountered using the 1/8-inch (0.3175-cm) slot, 11-percent open-area liner. The predominant frequency was 1400 hertz (second-longitudinal mode) with a peak also at 700 hertz (first longitudinal). Several other smaller peaks were noted at frequencies over 1500 hertz.

The 3/16-inch (0.48-cm) slot, 16.5-percent open-area liner (fig. 23(b)) depressed all modes above 2000 hertz to less than 10 psi (0.689 kN/m^2) peak to peak. The predominant mode was again first longitudinal with a peak at second longitudinal. The peak at 1800 hertz does not correspond to any conventional mode. Subsequent testing burned the slots wider and finally failed the partitions (fig. 24). The flame was not contained in the chamber when the wider, 3/16-inch (0.48-cm) slots were tested and it expanded into the backing cavity. As the slots widened, the liner became ineffective in damping the transverse modes. Therefore, it appears from these tests that a maximum slot width must be known such that the combustion can be confined to the chamber.

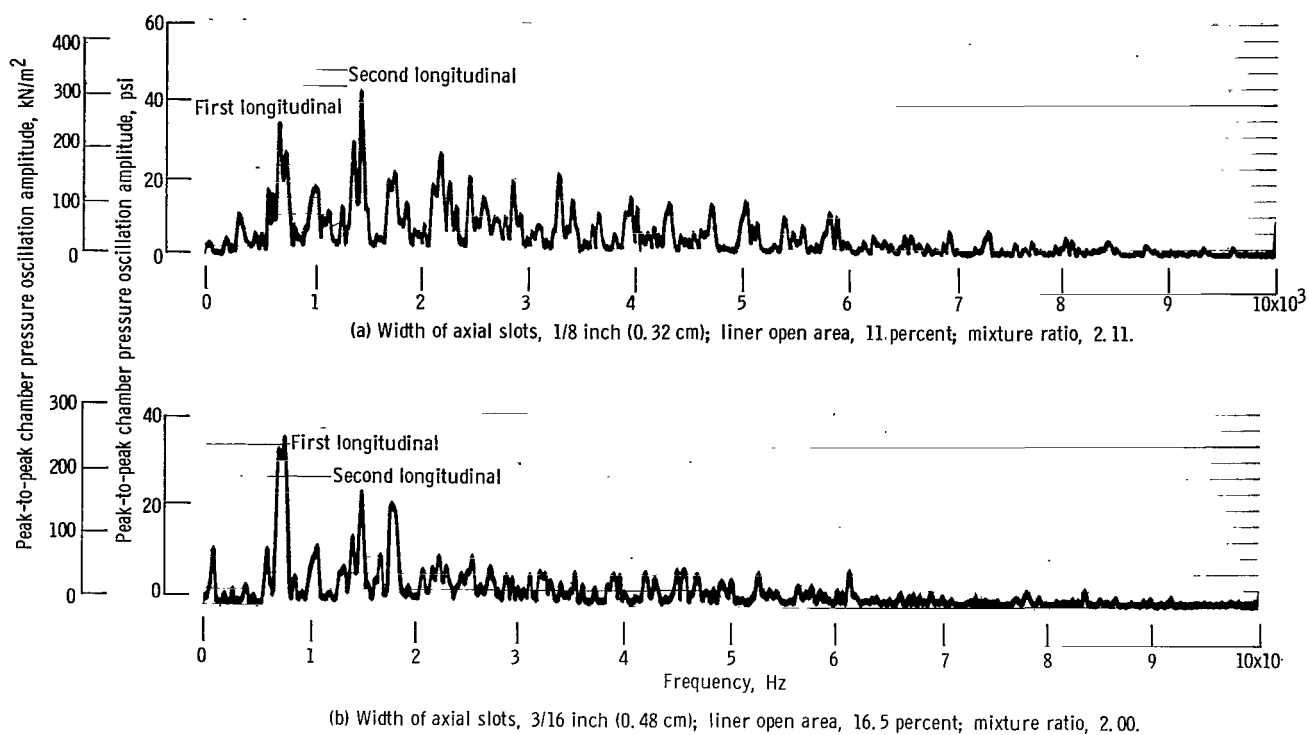
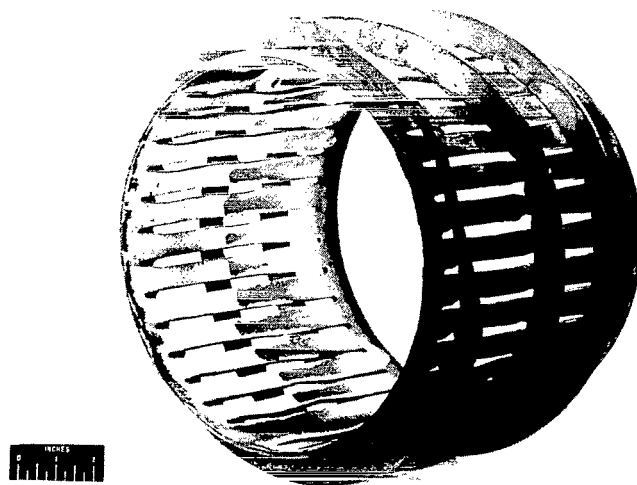


Figure 23. - Typical spectral density graphs of instability encountered combustor incorporating axial slot liners. Chamber characteristic length, 56 inches (142.2 cm).



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Figure 24. - Burned-out slot liner (3/16 in. (0.48 cm) wide).

In comparing figures 16 and 17 with figures 22 and 23, it can be seen that the slot liners ($P/A = 33.8$ and 17.2) performed at least as well as the circular aperture liners ($P/A = 32$ and 16). Similar to the tests of the circular aperture liners, absorption improved with increasing open area. If the effect is one of open area rather than slot width or P/A ratio, a liner using narrow slits (possibly $1/16$ in. (0.16 cm)), but at a higher percent open area (10 to 20 percent) would be more effective.

Cross shape aperture in 56-inch (142.2-cm) characteristic-length combustor. - The cross liners were designed with 10 percent open area. Each aperture had the same area, but the perimeter was varied to find an effect, if any, on the acoustic resistance which, in turn, affects the absorption (ref. 17). The two liners tested had arm widths of $1/32$ and $1/8$ inch (0.08 and 0.32 cm) ($P/A = 31.8$ and 10.0); other dimensions can be seen in table III. Although the first-longitudinal mode was predominant when the $1/8$ (0.32 cm), smaller P/A , liner was tested, other complex modes were observed from 1000 to 3000 hertz as seen in figure 25(a). A peak was also noted at 5100 hertz corresponding to the

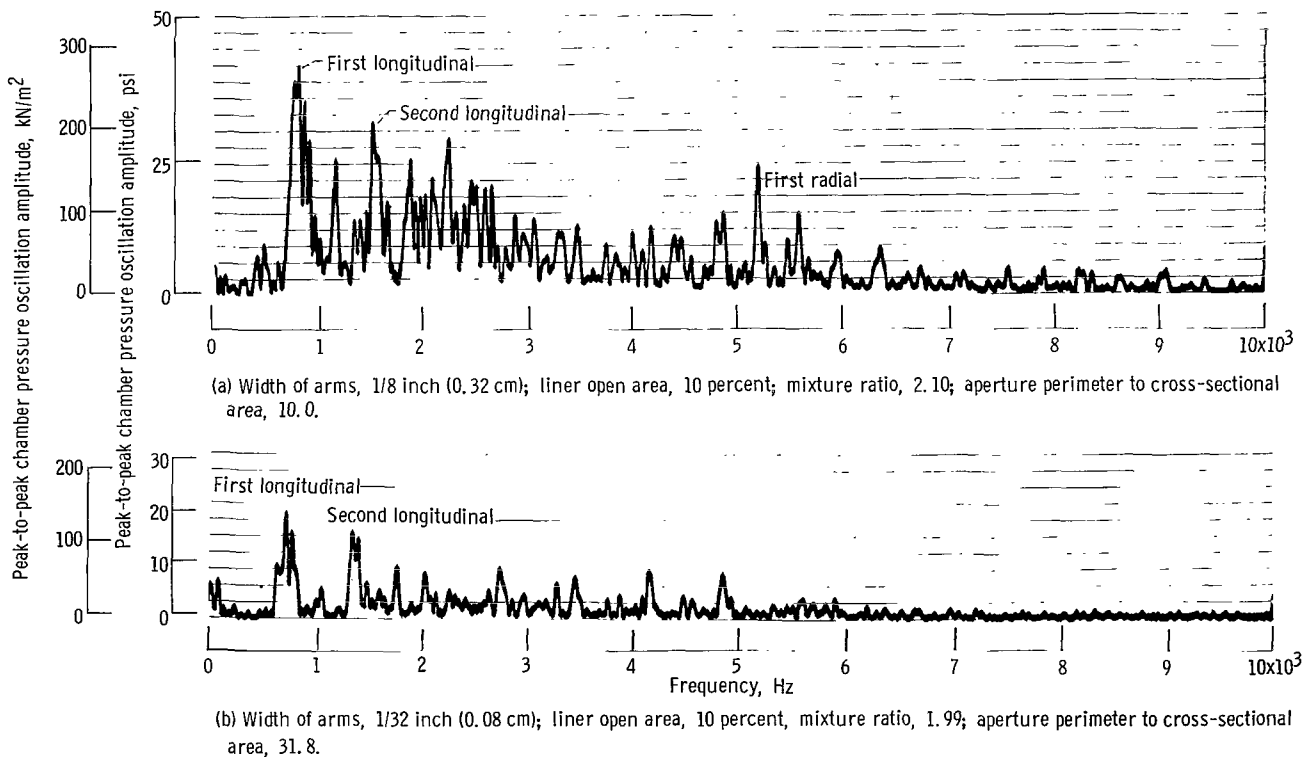


Figure 25. - Typical spectral density graphs of instability in combustors incorporating liners with cross-shaped apertures. Chamber characteristic length, 56 inches (142.2 in.).

first-radial mode. These modes were depressed, by the 1/32 inch (0.08 cm), larger P/A, liner (fig. 25(b)). The first-longitudinal mode was predominant and the other peaks are even multiples of this mode with the exception of 1800 hertz.

In general, the cross liner with the smaller P/A ratio (10.0) was less effective than the 19-percent open-area circular-aperture liners (P/A = 16 and 32). The larger P/A (31.8) liner was as effective as the circular aperture liners and also seemed to reduce the amplitude of the longitudinal modes. Therefore, there is an apparent effect of P/A ratio on liner damping characteristics.

Aperture shape bomb rating in 42-inch (106.7-cm) characteristic-length combustor. - Two liners were bomb rated for comparison with other bombing tests; they were the 5-percent open-area, full-length slot liner and the 10-percent open-area alternating-slit liner. The alternating-slit liner was not run in the 56-inch (172.2-cm) L* combustor because of burned out spots on the liner. All the bombs, up to the maximum of 41 grains (2.66 g), were damped by the full-length longitudinal-slot liner. The alternating-slit liner also damped all the bombs up to 41 grains (2.66 g) with one exception. A 41-grain (2.66-g) bomb drove the combustor into the first-tangential mode for 0.18 second and then damped out. The predominant mode (fig. 26) was at 2100 hertz with

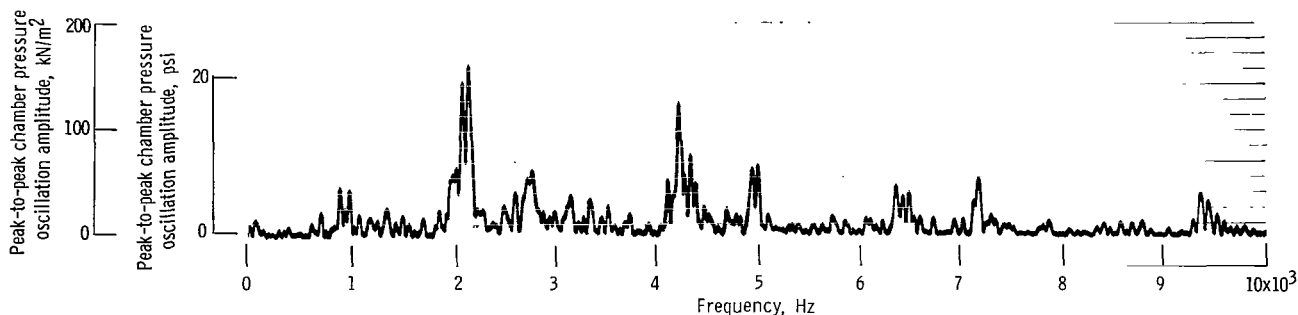


Figure 26. - Spectral density graph of unsustained instability induced in combustor. Type of aperture, alternating slits, 13/32 by 1/16 inch (1.03 by 0.16 cm); RDX bomb size, 41 grains (2.66 grams); mixture ratio, 1.60; duration of screech, 0.18 second.

a lower amplitude peak at 4200 hertz. The mode at 2100 hertz could be a shifted first-tangential, but it also corresponds closely to a second-longitudinal mode in 42-inch (106.7 cm) L* chamber. The alternating slit liner (P/A = 38.3) was comparable to the marginally stable 1/4-inch (0.64-cm) diameter aperture, 5-percent open-area liner (P/A = 16). The longitudinal slot liner (P/A = 44.8) damped all bombs and was comparable to the 1/8- and 1/4-inch (0.32- and 0.64-cm) diameter, 10-percent open-area liners (P/A = 32 and 16, respectively).

The stable operating backing-cavity-gas temperatures for these configurations agreed well with the values obtained with circular apertures at the same open areas. The

average temperature measured during the alternating-slit (10-percent open-area) tests was approximately 2400° R (1333° K) corresponding to the circular aperture average temperature of about 2450° R (1362° K). The average temperature measured in the 1/16-inch (0.16-cm) slot (5-percent open area) gap was 2000° R (1111° K), which is the average of the 1/8- and 1/4-inch (0.32- and 0.64-cm) diameter aperture temperatures at 5-percent open area. It can be assumed from these tests, therefore, that aperture shape and dimension have little effect on backing-cavity-gas temperature; percent open-area controls the temperature as long as combustion does not occur in the backing cavity.

Theoretical analysis of aperture shape variation data. - A comparison of the equations for the circular and noncircular aperture is given in table IV.

TABLE IV. - COMPARISON OF EQUATIONS FOR CIRCULAR
AND NONCIRCULAR APERTURES

Parameter	Circular apertures	Noncircular apertures
Resonant frequency, f_o	$\frac{12c}{2\pi} \sqrt{\frac{\sigma}{Ll_{eff}}}$	$\frac{12c}{2\pi} \sqrt{\frac{\sigma}{Ll_{eff}}}$
Effective length, l_{eff}	$t + 0.85 d(1 - 0.7\sqrt{\sigma})$	$t + \frac{2}{\pi} b \left(\ln \csc \frac{\pi\sigma}{2} \right)$ Ref. 18
Absorption coefficient, α	$\frac{4\theta}{(\theta + 1)^2 + X^2}$	$\frac{4\theta}{(\theta + 1)^2 + X^2}$
Acoustic resistance, θ	$\frac{4\sqrt{\pi\mu\rho f}}{\sigma\rho c} \left(\frac{t}{d} + \epsilon \right)$ $\epsilon = \left(1 + \frac{\Delta n l}{d} \right)$	$\frac{4\sqrt{\pi\mu\rho f}}{\sigma\rho c} \left[\left(\frac{t}{4} \times \frac{P}{A} \right) + \epsilon \right]$ Ref. 18
Acoustic reactance, X	$\frac{\omega_o l_{eff}}{12c\sigma} \left(\frac{f}{f_o} - \frac{f_o}{f} \right)$	$\frac{\omega_o l_{eff}}{12c\sigma} \left(\frac{f}{f_o} - \frac{f_o}{f} \right)$

Based on table IV, the two parameters chosen to characterize the liners are the liner resonant frequency f_o , the flow shifted resonant frequency f_{ov} , and the P/A ratio. Absorption coefficients were not calculated because of a lack of data for the empirical relation ϵ . The calculated values are presented in table V. As in the case of the circular apertures, the liners with resonant frequencies nearest the 5000-hertz screech frequency should perform best. However, the P/A ratio also increases the absorption by raising the acoustic resistance θ to a value nearer unity.

TABLE V. - CALCULATED APERTURE SHAPE EFFECTS

Aperture geometry	Aperture width		Open area, percent	Liner resonant frequency ^a , f_o , Hz	Flow past shifted resonant frequency ^a , f_{ov} , Hz	Aperture perimeter to cross-sectional area ratio, P/A	
	in.	cm				in. ⁻¹	cm ⁻¹
Axial slot	1/16	0.16	5	1870	2840	33.8	85.9
	1/8	.32	11	2940	4460	17.2	43.7
	3/16	.48	16.5	3660	5550	11.6	29.6
Cross	1/8	0.32	10	2750	4170	10.0	25.4
	1/32	.08	10	3180	4830	31.8	80.8
Alternating slit	1/16	0.16	10	3060	4650	38.3	97.3

^aPreferential wave (screech) frequency, 5000 Hz.

It can be seen in table V that the axial-slot liner with a small slot width has an unfavorable tuning ($f_o \ll 5000$ Hz) but has a favorable (large) P/A ratio, whereas a larger slot width has favorable tuning (f_o near 5000 Hz) while the P/A ratio is unfavorable (small). Test results indicated that the larger slit width performed best, which indicates the importance of tuning as compared with the effect of P/A ratio on resistance.

The 1/32-inch (0.08-cm) arm-width cross configuration has favorable tuning and a favorable P/A ratio as compared with the 1/8-inch (0.32-cm) arm configuration. Results of the tests indicate that the 1/32-inch (0.08-cm) configuration performed better.

The alternating-slit liner appeared to be a favorable design from both the tuning and resistance standpoints. The results indicate, however, only marginal stability compared with the 1/16-inch (0.16-cm) axial-slot liner. No explanation is possible at this time for the anomalous result.

In general, it can be concluded that the theoretical tuning and P/A ratio can predict the trends in liner damping with tuning the more influential factor.

SUMMARY OF RESULTS

Acoustic-liner tests to suppress screech in a rocket using storable propellants yielded the following results:

1. Combustors incorporating acoustic liners damped bomb pulses as high as 170 psi (1172 kN/m²) peak to peak, produced by 41-grain (2.66-g) bombs, whereas unlined com-

bustors could be driven unstable with RDX bombs as small as 6 to 8 grains (0.39 to 0.52 kg).

2. Acoustic liners damped high-frequency instabilities in a spontaneously unstable combustor, but the oscillatory energy was redistributed to low-frequency longitudinal modes because of the long combustor length (chamber characteristic length, 56 in. (142.2 cm)).

3. A combination of liners is required to suppress screech where widely separated transverse and longitudinal modes can exist, such as in long chambers, because of limitations in liner absorption bandwidth.

4. Tuning an acoustic liner to the unlined combustor screech frequency was essential for good absorption during these tests.

5. Backing-cavity-gas temperature increased with increasing percent open area and approached the boundary-layer gas temperature level at 20-percent open area. Circular aperture diameter had no significant effect on the gas temperature nor did the aperture shape when varied. The gas temperature was affected by percent open area and propellant combination.

6. Full-length combustor liners were not required for stable operation in the combustors used in this study. Liners of 1/4 chamber length also damped 41-grain (2.66-g) pulses, but the length required is apparently a function of liner absorption.

7. Although the perimeter to area ratio, P/A , of apertures affected absorption, tuning again appeared to be the controlling factor in absorption when shape was varied.

8. Axial slots were as effective as circular apertures and could be more readily adapted to a cooled configuration than circular apertures.

9. Agreement between experimental and theoretical results was possible assuming zero velocity past the apertures (circular) as well as assuming a Mach number of 0.24. A minimum absorption coefficient required for stable operation was calculated to be 10 percent for zero Mach number using the analysis described herein. The flow past case ($M/0.24$) increased the required absorption coefficient by about 50 percent. An assumed flow at Mach 0.11 was required to correlate this data with that reported in reference 5 (i.e., minimum absorption coefficient of 25 percent).

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, September 21, 1967,
128-31-06-05-22.

APPENDIX - SYMBOLS

b	slit resonator aperture width, in. ; cm	α	absorption coefficient, dimensionless
C*	characteristic exhaust velocity, ft/sec; m/sec	Δ_{nl}	nonlinear resistance term, in. ; cm
c	sonic velocity in resonator, ft/sec; m/sec	$\Delta f_o/f_o$	resonant frequency flow past shift term, dimensionless
d	aperture diameter, in. ; cm	ϵ	nonlinear resistance parameter, dimensionless
f	screech or design frequency, Hz	θ	acoustic resistance, dimensionless
L*	chamber characteristic length, in. ; cm	μ	viscosity of resonator gas, lb _m /(ft)(sec); (N)(sec)/m ²
ℓ	liner backing cavity height, in. ; cm	ρ	density of resonator gas, lb _m /ft ³ ; kg/m ³
l_{eff}	liner aperture effective length, in. ; cm	σ	liner open area ratio
O/F	oxidant-fuel mixture ratio	ω	angular frequency, rad/sec
P/A	aperture perimeter to cross sectional area ratio	Subscripts:	
t	liner thickness, in. ; cm	o	liner resonant frequency
X	acoustic reactance, dimensionless	ov	flow past shifted resonant frequency

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